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THE FLUORESCENT AND ABSORPTION SPECTRA OF ANTHRACENE AND PHENANTHRENE VAPORS

By T. SIDNEY ELSTON

I. INTRODUCTION

The fluorescence of vapors was first observed by Lommel[1] for iodine vapor in 1883. A few years later Ramsay and Young[2] and E. Wiedemann[3] found that some liquid solutions, when raised above their critical temperatures, fluoresce. Later, Wiedemann and Schmidt[4] discovered a long list of fluorescent organic vapors, among which were anthracene and phenanthrene. They found that these vapors under the action of sunlight or light from a carbon arc fluoresced an intense blue, the fluorescent light lying, as a whole, on the red side of the region of maximum absorption. In 1896 they[5] discovered also that the metallic vapors of sodium and potassium are fluorescent. Quite recently Professor R. W. Wood[6] has made an extensive study of the fluorescence of sodium vapor. Hartley[7] has shown that mercury vapor also is fluorescent under certain conditions.

With the exception of sodium vapor, none of these vapors had been investigated extensively for its fluorescence; and yet it seemed

[1] *Wied. Ann.*, **19**, 356, 1883.
[2] *Chem. News*, **54**, 203, 1886.
[3] *Wied. Ann.*, **41**, 209, 1890.
[4] *Ibid.*, **56**, 18, 1895.
[5] *Ibid.*, **57**, 447, 1896.
[6] *Phil. Mag.*, **10**, 513, 1905.
[7] *Proc. R. S.*, **76** A, 428, 1905.

desirable that such work should be done, for the sake of the aid which it might afford for the solution of the problem of luminescence, and ultimately of the problem of the nature of matter. In the present investigation the primary object was to study in more detail the fluorescence of anthracene vapor, one of the very strongly fluorescent organic vapors. Later a similar study was made of phenanthrene because of the close resemblance between its fluorescent spectrum and that of anthracene, its isomer.

II. THE FLUORESCENT SPECTRUM OF ANTHRACENE VAPOR

a) *Method and apparatus.*—The fluorescence of the anthracene vapor was first studied by means of a small quartz spectrograph. The pure anthracene used was obtained from the commercial product by distilling twice from an excess of caustic potash, and then crystallizing from benzene under the action of the sunlight. A few centigrams of the crystals were inclosed in a crown-glass bulb (5 to 8 cm in diameter), which was then evacuated and sealed.

The bulb was placed in a heating apparatus arranged as shown in Fig. 1. It was hung in a wire cage between the two side tubes, T_1 and T_2, in such a manner that the light employed to excite fluorescence, after passage through the condensing lens, L, and reflection from the mirror, M, downward through the mica window, W, was focused at the center of the bulb.

The tube, T_1, contained a rectangular opening at its inner end and a glass window near its outer end. When the bulb was heated and the anthracene made to fluoresce, the fluorescent light was examined by the spectrograph through this tube.

The larger tube, T_2, provided with a cap over its outer end, served a double rôle: first, as an observing tube for adjusting the apparatus so as properly to focus the light in the bulb; and, secondly, as a dark background against which to observe the fluorescence through the other tube, T_1.

Care was always taken to adjust the bulb so that the cone of exciting light should be reflected from the bottom of the bulb straight back along its path. This was done in order to get rid, as far as possible, of the light scattered by reflection from the sides of the bulb. It was found, when bulbs of the proper size and shape were adjusted

in this way, that an exposure of three hours, made for scattered light alone, gave a very faint photograph as compared with that of the fluorescent and scattered light combined.

Various sources of violet and ultra-violet light were tried—viz., the sun, the carbon and zinc arcs in air, the mercury, silver, and lead arcs *in vacuo*, and the cadmium, aluminium, copper, zinc, and magnesium sparks. Of these the carbon arc produced the most

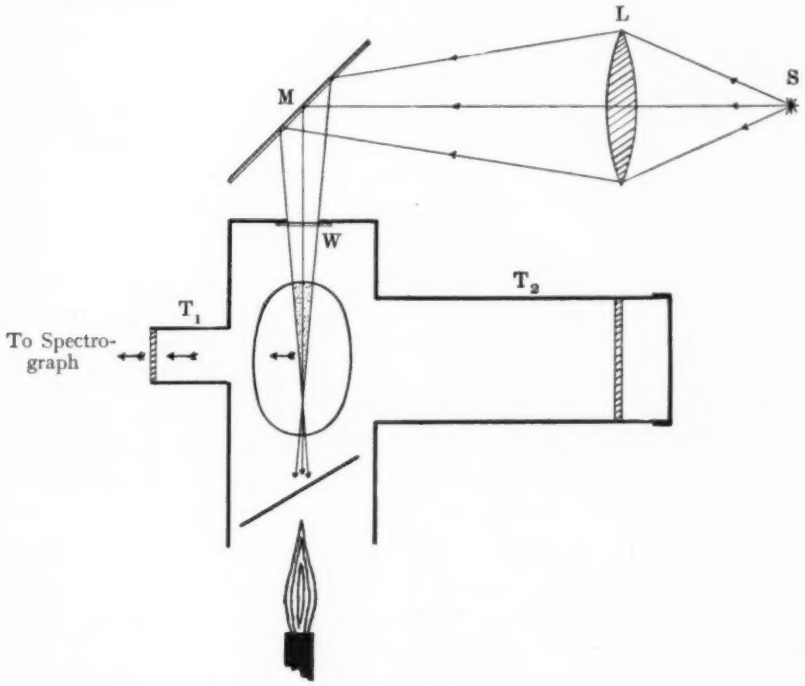


FIG. 1

intense fluorescence in the anthracene vapor, and so was employed almost exclusively. It was found that the fluorescence was due more to the light from the incandescent gases between the carbons than to the incandescent carbons themselves. Its intensity increased or decreased with the intensity of the group of three cyanogen bands in the violet.

b) *The fluorescence.*—When the bulb was heated until the anthracene began to vaporize, the path of the arc-light through it was

marked by a cone of illuminated particles which scattered partially polarized white light in all directions. Gradually this disappeared as the anthracene became completely vaporized, and was replaced by a cone of brilliant blue fluorescent light in which no polarization could be detected. Examined photographically with the quartz spectrograph, it gave a spectrum (Plate X, 1*a*) which extended continuously from 365 $\mu\mu$ to 470 $\mu\mu$, with its regions of maximum intensity located at 390, 415, and 432 $\mu\mu$. The same spectrum was also obtained when sunlight, or the light from any of the other sources was employed as the exciting light.

The range of the apparatus was from λ 325 to 540 $\mu\mu$, the limit in the ultra-violet being set by the crown glass of the bulb which is opaque to radiation of wave-length shorter than 325 $\mu\mu$.

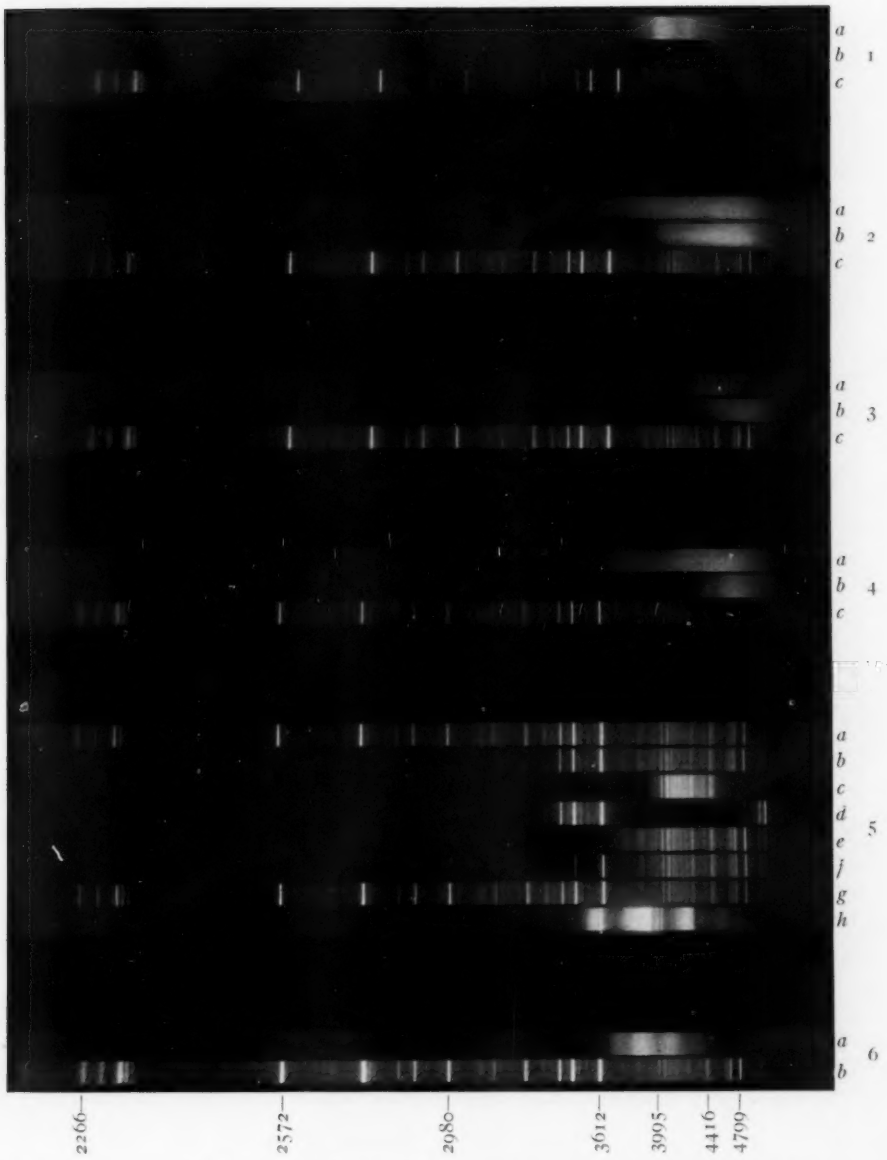
The photograph did not show the slightest evidence of lines in the fluorescent spectrum. This, it was thought, might be due to the small resolving power of the quartz spectrograph in the region of the fluorescence; so a photograph was taken with a special, three-crown-prism spectrograph, designed by Professor Wood for his work on sodium vapor. The resolving power of this instrument was about fifteen times that of the quartz spectrograph; but in this case also the photograph failed to show any lines in the spectrum. The fluorescence was not intense enough to warrant the use of instruments of higher resolving power. It seems highly probable, however, that the fluorescent spectrum of anthracene vapor is not resolvable into lines like that of sodium vapor, but resembles, instead, the banded spectra of fluorescent liquids and solutions.

III. THE EFFECT OF INCLOSING A FOREIGN GAS WITH THE ANTHRACENE

To determine what effect upon the fluorescence the presence of another gas would have, the anthracene was inclosed in the bulb in turn with various gases at atmospheric pressure. It was found that some gases had practically no effect, while others extinguished the fluorescence more or less completely. The results are given in the accompanying table.

In the case of the gases listed in the first column of the table the quality of the fluorescence was unaffected by their introduction into

PLATE X



FLUORESCENT AND ABSORPTION SPECTRA OF ANTHRACENE AND PHENANTHRENE VAPORS

1. *a*, Fluorescence of Anthracene; *b*, Diffused Light; *c*, Cadmium Spark.
2. *a*, Nernst Filament; *b*, Absorption of Anthracene; *c*, Cadmium Spark.
3. *a*, Nernst Filament; *b*, Absorption of Anthracene (dense vapor); *c*, Cadmium Spark.
4. *a*, Nernst Filament; *b*, Absorption, Commercial Anthracene; *c*, Cadmium Spark.
5. *a*, *g*, Cadmium Spark; *h*, Carbon Arc Spectrum; *d*, Solution A as screen; *e*, Solution B; *e*, Solution C; *b*, Crown-Glass Plate as screen.
6. *a*, Fluorescence of Phenanthrene; *b*, Cadmium Spark.

FLUORESCENCE OF ANTHRACENE VAPOR

Not Affected by	Extinguished by	Weakened by
Nitrogen	Cyanogen	Air
Hydrogen	Chlorine	
Illuminating gas	Sulphur dioxide	
Carbon monoxide	Oxygen	
Carbon dioxide		
Mercury vapor		

the bulb. A slight decrease in intensity, however, was observed, due, probably, to the higher pressures in the bulb after the gases were introduced (see § IV). So far as could be ascertained, none of these gases reacts chemically upon the anthracene vapor within the range of temperatures set by the apparatus.

In the case of the gases listed in the second column the effect was practically to extinguish the fluorescence. Only the faintest trace, if any, of fluorescence could be observed when they were mixed with the anthracene. For these gases it was found that chemical action began either as soon as the temperature was raised to a point where the anthracene was vaporized (this was the case with cyanogen and chlorine), or at a temperature not much higher (this was the case with sulphur dioxide and oxgyen). It seemed highly probable from this that the extinction of the fluorescence was due to some sort of chemical influence.

That the chemical influence, if such it be, which affected the fluorescence, need not be such as to produce a permanent chemical change in the anthracene was shown in the following way: A bulb containing anthracene and oxygen was placed in an air-bath with a similar bulb containing only anthracene. The temperature was then raised just high enough to obtain strong fluorescence in the second bulb, but not high enough to cause any visible chemical reaction between the oxygen and the anthracene in the first bulb. The first bulb was tested for fluorescence and found not to show the slightest traces. It was then removed and the oxygen pumped out, the crystallized anthracene being left behind, and the bulb again placed in the bath and tested. The fluorescence in this bulb was now found to be as brilliant as in the other one. To find out if some of the anthracene had not been acted upon and a consequent change in

volume of the oxygen produced, a bulb was used which terminated in a long capillary tube. The oxygen gas and anthracene crystals were inclosed at atmospheric pressure and the bulb sealed. Then, after subjecting the bulb to the same heating as before, the end of the capillary tube was broken off under mercury, and the oxgyen again brought to atmospheric pressure. Not the slightest change in its volume was observed. If any chemical action had occurred, it was evidently of such a nature as to produce compensating changes in the volume of the reacting substances. As this is highly improbable, we are led to conclude that no reaction took place between the anthracene and the oxygen, but that whatever mutual action occurred produced effects which lasted only while the given conditions of temperature and mutual contact were maintained. During this time practically all of the anthracene molecules must have been affected, for the extinction of the fluorescence was complete throughout the vapor.

The foregoing facts may be explained by assuming that, when anthracene vapor is mixed with oxygen at a temperature not much below that at which the two react chemically, there is a preliminary grouping of the oxygen molecules about the anthracene molecules, or vice versa, and that, while thus associated and before they rush together into closer contact to form a new chemical compound, the mutual forces are such as to prevent the anthracene molecules from fluorescing, but are not great enough to bring about a reaction. As thus considered, the phenomenon is simply the first stage of a chemical reaction.

The effect of oxygen upon the anthracene vapor is in many ways similar to that of many liquid solvents upon the fluorescent substances dissolved in them.[1]

When the vapor was mixed with air, the fluorescence was much weakened, becoming almost too weak to be seen when air at atmospheric pressure or greater was used. This weakening was easily traceable to the oxygen contained in the air.

It seems highly probable from the foregoing facts that the presence of foreign molecules, heavy or light, among the fluorescing anthracene molecules does not have any appreciable effect upon the

[1] Kauffmann and Beiswenger, *Zeitschrift für phys. Chem.*, **50**, 350, 1904.

fluorescence at ordinary pressures, except in those cases where a chemical change, either incipient or permanent, occurs.

IV. THE EFFECT OF PRESSURE

In the experiment with the illuminating gas a thick-walled glass bulb was employed, and the pressure was varied from 1 to 12 atmospheres. The visible fluorescence became less and less intense as the pressure was increased, but was still perceptible at the highest pressure. So far as this was tried with the other gases, the same results were obtained, an increase of pressure in each case causing a diminution in the intensity of the fluorescence. The change in intensity was not very marked until the pressure exceeded 1 atmosphere. At all pressures below this the intensity of the fluorescence was practically independent of the pressure.

The quality of the fluorescence was not affected by the pressure; the same spectrum was obtained at high as at low pressures.

V. THE EFFECT OF TEMPERATURE

The temperature of the bulb was varied from the temperature at which the vapor began to fluoresce (the boiling-point of anthracene is 351° C.) to the temperature at which the glass began to soften (the melting-point of the glass bulb is about 1000° C.). As the temperature was raised the intensity of the fluorescence diminished. This was the case whether the bulb contained the pure anthracene alone or anthracene mixed with an inert gas. Of course, as the temperature was raised, the pressure of the inclosed vapor was increased; so the effect may have been due to this.

VI. THE EFFECT OF VARYING THE DENSITY OF THE VAPOR

When the amount of anthracene inclosed in the bulb was gradually increased, and the vapor density thus correspondingly increased, it was found that the cone of visible fluorescence, which at first extended completely through the bulb from the point where the exciting light entered to the point where it left, was foreshortened in the direction of its length, until finally it was shrunk down almost to the surface where the exciting light entered the bulb. At the same time the intrinsic brightness of the fluorescence was diminished, due, undoubtedly, to the consequent increase in pressure.

The foreshortening of the cone of fluorescence means, of course, that the particular radiation which excites the visible fluorescence is completely absorbed out of the incident light before this penetrates very far into a bulb filled with dense anthracene vapor.

The quality of the fluorescence was not affected, as the spectrum photographs for bulbs containing different amounts of anthracene showed.

VII. THE ABSORPTION SPECTRUM

To obtain the absorption spectrum of the vapor, it was found convenient to use a long glass tube in which to inclose the anthracene. This was placed inside a cylindrical iron tube with a glass window at each end, as shown in Fig. 2.

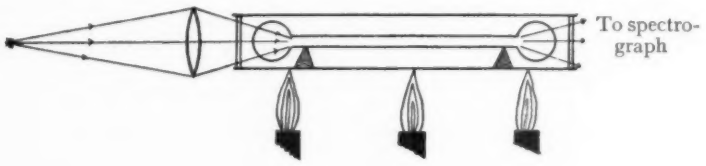


FIG. 2

The light from a Nernst filament was focused in the tube at one end, and, on emerging at the other end, was examined photographically with the quartz spectrograph.

The photograph (Plate X, 3*b*) was taken when the anthracene vapor in the tube was quite dense. It shows that the pure dense vapor absorbs continuously from λ 425 to 325 $\mu\mu$, the limit set by the crown glass. When the tubes containing less anthracene, or the bulbs employed in getting fluorescence, were used, the absorption did not extend so far down toward longer wave-lengths (Plate X, 2*b*).

The absorption of the vapor was also studied with a 12.5-foot concave Rowland grating, but with the same result. There was no evidence of lines in either case; the absorption consisted of a continuous region between λ 325 $\mu\mu$ and about 425 $\mu\mu$.

Purified anthracene was used in obtaining the absorption spectra just described. When the commercial anthracene (Eimer & Amend, 90 per cent.) was used, the absorption spectrum obtained (Plate X,

4*b*) was found to be the same as for the pure anthracene, with the exception that there was a narrow band at wave-length 452 $\mu\mu$.

VIII. THE RELATION BETWEEN THE EXCITING LIGHT AND THE FLUORESCENCE—STOKES'S LAW

1. *The carbon arc as source.*—In the earlier stages of the investigation (when the fluorescent spectrum was excited by the light from a carbon-arc lamp and the photograph taken showed that it consisted of three bands which were somewhat similarly spaced, but farther toward the red, as compared with the three intense cyanogen bands of the arc in that region of the spectrum), it was thought probable that the three cyanogen bands had each excited its own fluorescent band in the anthracene vapor, thus giving rise to the three bands found in the fluorescent spectrum. The fact, that sunlight excited the same bands seemed to make this doubtful; but it was not until the work, now to be described, was done that it was shown that, in all probability, the entire fluorescence of the vapor excited by light from the carbon arc was largely due to the strong lines in the head of the middle one of the three cyanogen bands, the one whose head lies at wave-length 388.3 $\mu\mu$.

Two methods were employed in determining the approximate wave-length of the exciting light.

a) The first to be tried was what might be called the "method of exclusion." It consisted in screening off different portions of the spectrum in turn, by means of properly chosen absorbing solutions, and observing the effect upon the fluorescence. By referring to Dr. Uhler's photographs of the absorption spectra of various solutions, the following solutions were chosen and found to answer the purpose:

A. Nitroso-dimethyl-aniline solution, 2 parts by volume of saturated solution to 3 parts of water.

B. Potassium permanganate solution, 1 part by volume of saturated solution to 50 parts of water.

C. Naphthol disulfonic acid solution, 2 parts by volume of saturated solution to 5 parts of water.

These solutions were introduced into a glass cell (1 cm thick) which was placed in the path of the exciting light between the condensing lens (see Fig. 1) and the bulb.

When solution A was employed as an absorbing screen, the anthracene vapor failed to fluoresce. Now, this solution has a strong absorption band extending from 375 to 480 $\mu\mu$ (see Plate X, 5*d*), while it transmits quite freely on both sides of the band, within the limits set by the glass. It is evident from this that the light which causes the fluorescence in the vapor is located somewhere in the region 375–480 $\mu\mu$. It is in this region that two of the cyanogen bands are located; the third lies just outside of it toward the ultra-violet.

The solution B is transparent to light of wave-length 395–465 $\mu\mu$, but is quite opaque to the rest of the spectrum in the given region. When this solution was substituted in the cell for solution A, no fluorescence could be observed. This shows that the light producing the fluorescence does not lie between 395 and 465 $\mu\mu$, and therefore must lie either in the region 465–480 $\mu\mu$, or in the region 375–395 $\mu\mu$, or in both. That it does not lie in the region 465–480 $\mu\mu$ is probable from the fact that the carbon arc spectrum is relatively weak in this region. We are then led to conclude that the exciting light lies somewhere between the wave-lengths 375 and 395 $\mu\mu$. It is in this region that the strong lines in the middle one of the three cyanogen bands are located.

b) A confirmation of the foregoing results was obtained in the following way: A slit, two condensing lenses, and a large crown-glass prism were arranged so as to give a comparatively pure and bright spectrum of the arc. A slitted screen, with the bulb containing the anthracene vapor behind it, was then passed from point to point along through the spectrum. Starting at the red end there was no visible evidence of fluorescence in the vapor until the bulb was brought into that part of the spectrum corresponding to wave-lengths 390–375 $\mu\mu$, when it began to fluoresce with the characteristic brilliant blue color, the cone of fluorescence extending entirely through the bulb. When moved on into the region of the cyanogen band whose head is at 359 $\mu\mu$, a dim fluorescence was observed which penetrated only a few millimeters into the bulb. It had played small part, therefore, in the photographs of the fluorescent spectrum previously taken, where the collimator of the spectrograph had been directed toward the center of the bulb.

The slitted screen was now adjusted so as to allow only the light

near the head of the cyanogen band at 388.3 $\mu\mu$ to enter the bulb. A photograph of the fluorescence produced was taken which gave the same bright bands and continuous regions shown in the former photographs (see Plate X, 1*a*).

The slit was then moved so as to admit to the bulb the head of the cyanogen band at 359 $\mu\mu$, and a photograph of the fluorescence was taken. It showed that the spectrum was the same as that excited by the other cyanogen band.

The relative spectral positions of the fluorescence and the exciting lights for the two experiments just described are shown in Fig. 3. The block E_1 represents the spectral width and location of the exciting light in the first experiment, and F_1 the general form of distribution of intensity in the fluorescence which it excited in the anthracene vapor, while E_2 and F_2 represent the corresponding quantities in the second experiment. The two curves have been deduced from the photographs and indicate that the fluorescence in the two cases was the same in every way except in absolute intensity.

2. *The zinc arc and magnesium spark as sources.*—To obtain further evidence of the relation between the fluorescence and the wave-length of the light which excites it, two sources were employed which gave regions of exciting light quite widely separated. The first was the zinc arc, which gives an isolated group of very intense lines in the region 328–335 $\mu\mu$, just within the ultra-violet limit set by the absorption of the crown-glass bulb; the second was the magnesium spark, which gives an intense isolated triplet in the region 383–385 $\mu\mu$, not very far from the limit toward the red beyond which the light ceases to have power to excite fluorescence in the anthracene vapor. This limit was earlier found to be in the neighborhood of wave-length 400 $\mu\mu$.

Between 325 and 400 $\mu\mu$ the arc-spectrum of zinc contains, besides the group just mentioned, only three very faint lines whose aggregate intensity is less than 1 per cent. of that of the group. If the zinc arc is used, therefore, to excite the fluorescence in the anthracene, the exciting light is practically all located in the region 328–335 $\mu\mu$. When this was done (the zinc arc being substituted for the carbon arc) and the fluorescence produced in the bulb was photographed, it was found to give the same fluorescent spectrum as the carbon

arc. The block E_3 and the curve F_3 in Fig. 3 represent respectively the exciting light and the fluorescence for this case.

In the case of the magnesium spark there are a few faint lines in the region 325–400 $\mu\mu$ besides the triplet mentioned, but their aggre-

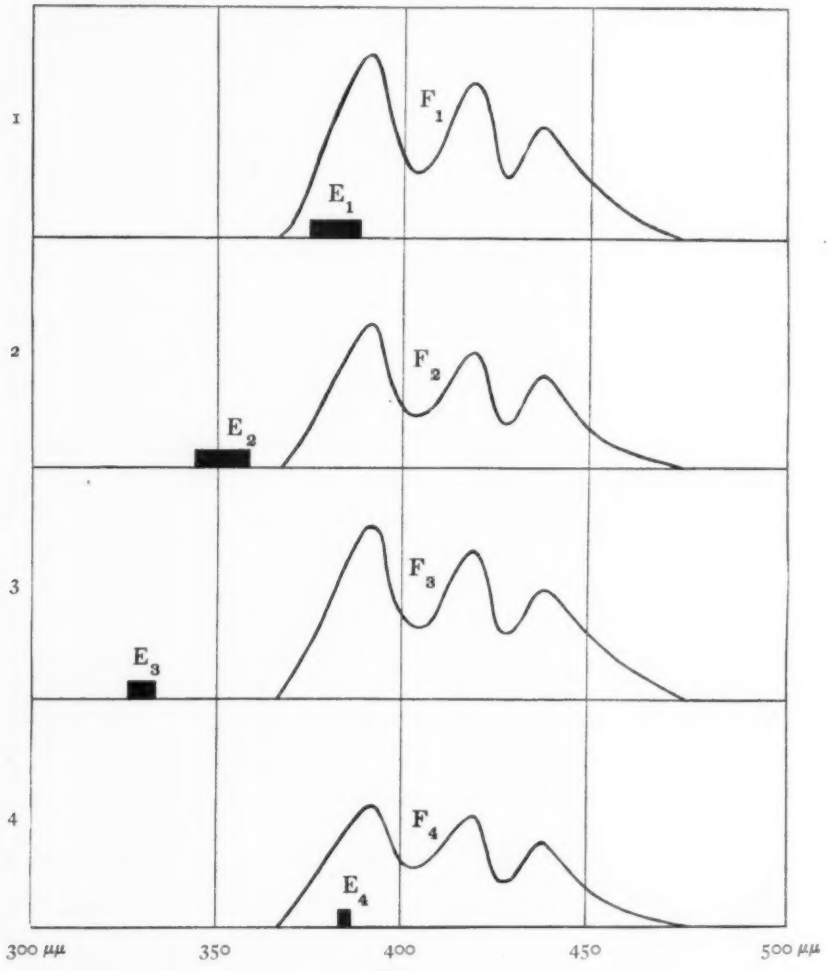


FIG. 3

gate intensity is negligible in comparison with that of the triplet, so that practically all of the exciting light from a pure magnesium spark is in the region 383–385 $\mu\mu$. It was found, however, that the elec-

trodes used contained zinc as an impurity. In order to screen off the lines due to the zinc, the solution C (see § VIII, 1) was used as an absorbing screen. It is opaque to ultra-violet light from 360 on out beyond 325 $\mu\mu$, and therefore to the group of zinc lines at 328–335 $\mu\mu$. When the magnesium spark, as thus screened, was used as the source and the fluorescence excited was photographed, it was found to give the same spectrum as the carbon and zinc arcs. The block E_4 and the curve F_4 in Fig. 3 represent respectively the exciting light and the fluorescence for this case.

In connection with the results given above, it should be remembered that the anthracene vapor used absorbs continuously from about 400 $\mu\mu$ to some point beyond 325 $\mu\mu$.

3. *Stokes's law.*—It is evident from the foregoing facts that Stokes's law, which states that the fluorescent light is of longer wave-length than the light which excites it, is not strictly true in the case of anthracene vapor; for in at least two cases (1 and 3 in Fig. 3) part of the fluorescent light is of shorter wave-length than the corresponding exciting light. In a general sense, however, the law may be considered as fairly representing the facts, since the fluorescent spectrum as a *whole* is of longer wave-length than the exciting light.

4. *Discussion of results.*—We are led to conclude from the foregoing facts (*a*) that the fluorescence of anthracene vapor is excited by light situated anywhere in the ultra-violet region of absorption of the vapor, and (*b*) that the character of the fluorescence is entirely independent of the source and wave-length of the light which excites it.

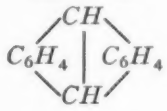
If we assume that the fluorescence is produced by a system of electrons within the molecule, then, in order to account for the fluorescent spectrum of anthracene vapor, which, as we found, was composed of three bands superposed upon a continuous spectrum, we may consider either that the electrons corresponding in period to the three bands are more numerous than those which give rise to the weaker, continuous parts of the fluorescence, or that the former are set in more violent vibration; also, that the system of electrons is so intimately connected in its parts that, when disturbed by the exciting light in any manner, be it direct or through an intermediary "luminophore," *all* the electrons in the system are set in vibration. If the disturbance of the system takes place through an intermediary

"luminophore,"[1] as seems more probable, then this luminophore undoubtedly consists of a connected system of electrons whose periods correspond to those of the absorption spectrum of the vapor.

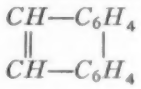
IX. THE FLUORESCENCE AND ABSORPTION OF PHENANTHRENE VAPOR, THE ISOMER OF ANTHRACENE VAPOR

Phenanthrene is a substance which has the same chemical composition, $C_{14}H_{10}$, as anthracene, but a slightly different structural composition as the following figure shows:

Anthracene



Phenanthrene



The only difference in structure, according to this, is in the manner in which the four groups or radicals are linked together.

When the fluorescent spectrum of pure phenanthrene vapor was photographed (Plate X, 6*a*), it was found to consist of the same bands as that of anthracene, but with an additional band at 360 $\mu\mu$.

Its absorption spectrum was photographed and found to be the same as that of the anthracene vapor.

It would seem from these facts that there is an intimate connection between the fluorescence of the vapors of the two substances, undoubtedly due to their common chemical composition and similar structural composition. Just what gives rise to the extra band in the fluorescent spectrum of phenanthrene vapor is not apparent.

X. SUMMARY

The following is a summary of the results of this investigation:

(1) The fluorescent spectrum of anthracene vapor consists of three bright bands at λ 390, 415, and 432 $\mu\mu$ superposed upon a continuous region extending from 365 to 470 $\mu\mu$. There is no evidence of lines. The absorption spectrum extends continuously from about 400 $\mu\mu$ to some point beyond 325 $\mu\mu$.

(2) The presence of inert gases in the vapor does not affect the fluorescence, so long as the pressure is below an atmosphere. But

[1] W. Kauffmann, *Ber. d. Phys. Gesell.*, **21**, 375, 1905.

such gases as oxygen, chlorine, and sulphur dioxide, which at high temperatures react chemically with anthracene, almost completely extinguish the fluorescence at ordinary pressures.

(3) The intensity of the visible fluorescence decreases as the pressure of the gas inclosed with the anthracene is increased. It is not marked, however, at pressures lower than an atmosphere. The quality of the fluorescence is not affected by a change in pressure.

(4) Increasing the density of the fluorescing vapor has no effect upon the quality of the fluorescence, but diminishes its intensity slightly.

(5) The fluorescence of anthracene vapor may be excited by l'ght located anywhere within the ultra-violet region of absorption of the vapor.

(6) The same fluorescent spectrum is produced independent of what the source or wave-length of the exciting light may be, provided the condition noted in (5) is observed.

(7) There is an intimate connection between the fluorescence of anthracene vapor and its isomer, phenanthrene vapor.

This investigation was begun at the suggestion and has been carried out under the direction of Professor R. W. Wood, to whom I wish to extend my thanks for the interest which he has shown, and the encouragement and help which he has given me in the course of the work. I wish also to express my gratitude to Professor J. S. Ames for his unfailing courtesy and kindness.

JOHNS HOPKINS UNIVERSITY

ON THE RADIATION OF CANAL RAYS IN HYDROGEN

PART II. LINEAR SPEED AND INTENSITY OF RADIATION[1]

By J. STARK

§ 11. *Ionization behind the cathode; origin of the banded spectrum and of the stationary line-spectrum.*—Referring to Fig. 8, K is a cathode made of wire net having one mesh to the millimeter; in that portion of the tube which lies behind the cathode and which is traversed by the canal rays are introduced two pointed electrodes; with these are connected in series a four-volt battery and a galvanometer. The cathode is earthed. So long as no canal rays pass between the wire electrodes, the galvanometer shows no deflection; when they begin to pass, however, the galvanometer indicates a current and hence conductivity in the gas.

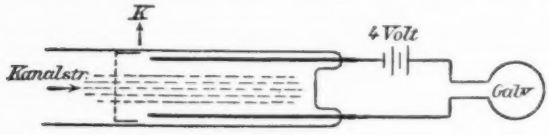


Fig. 8

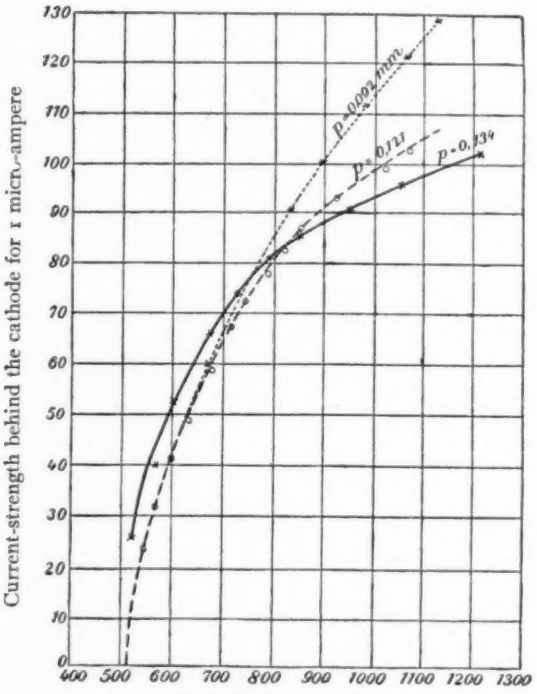


Fig. 9

In Fig. 9 are represented graphically three series of measurements, at three different pressures, in nitrogen. The cathode-

[1] Continued from page 44, January 1907.

drop in volts is plotted along the axis of abscissae; while the ordinates indicate the ratio of the current passing through the galvanometer to the current in the tube (*Glimmstrom*) which produces the canal rays.

It may be seen from the figure that, in the gas behind the cathode, the canal rays produce conductivity, and hence positive and negative ions; from 500 volts up the conductivity in the rear of the cathode rises at first rapidly, then more slowly, with the cathode-drop.

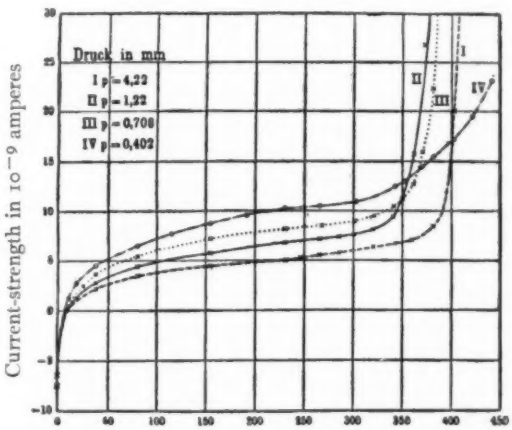

Druck in mm
I p = 4,22
II p = 1,22
III p = 0,708
IV p = 0,402
Current-strength in 10⁻⁹ amperes
Difference of potential between cathode and negative end of thread

FIG. 10

Fig. 10 has already been published in another place.[1] It was obtained as follows. A copper wire was placed opposite to the incandescent filament of a very small electric lamp, at a distance of 6 mm; this copper wire served as cathode, the incandescent carbon filament as anode. On this there will be produced some positive ions in consequence of the high temperature; and these will be driven to the cathode by the potential difference, ΔV, between the electrodes; when the gas-pressure is low they will traverse this drop in potential freely—i. e., without collision—and will strike the surface of the cathode, with high speed, as "canal rays." It is evident that for small potential differences the current will be small and nearly "saturated." At the velocity corresponding to about 340 volts, however, the positive ions, by the suddenness of their impact upon the cathode, begin to create new ions; and hence the current suddenly rises to large values.

It would thus appear that canal rays when moving with a speed

[1] J. Stark, *Verhandl. d. deutsch. phys. Ges.*, **6**, 104, 1904.

less than a certain limit (300 to 500 volts) are unable to ionize a gas by collision; with higher velocities, however, the gas is ionized. In the spectroscopic observations here described the cathode-drop always exceeded 1000 volts, so that the canal rays were capable of ionizing the gas behind the cathode, thus giving opportunity for the reunion of positive and negative ions, and hence, in terms of our hypothesis, for the emission of a banded spectrum. This radiation, then, has its origin in the potential energy which is set free by the reunion; it is an indirect consequence of the collision of the canal rays with the neutral atoms of the gas; the more frequent these collisions—i. e., the greater the gas-pressure—the more intense is the banded spectrum in the region traversed by the canal rays.

It has already been established, in §3, that the line-spectrum of this same region has both a displaced and a stationary intensity; the intensity of the line-spectrum in the negative glow is, at low temperatures, only stationary; no Doppler effect is here observable. In the region of the canal rays the stationary lines present the same appearance as the corresponding lines in the negative glow; and here the intensities of the series lines also diminish from red to violet in the same manner. In the negative glow the neutral atoms are ionized by collisions with cathode rays; behind the cathode they are ionized by collisions with canal rays. In the former case the newly formed positive ion always remains at rest because the mass of the incident cathode ray is so small; in the latter case either the ion just produced or the ion of the incident canal ray may remain at rest after the collision. Both cases have the feature in common that immediately after collision there is present a stationary positive ion. It is possible that this ion will be deformed by the collision, and will also have its internal energy increased—energy which it radiates immediately after the blow and while still at rest. We are thus led to infer that the stationary intensity of the line-spectrum has its origin in the deformation of a positive atom by collision. We may, therefore, infer that the stationary intensity of the line-spectrum is proportional to the number of collisions, and hence also proportional to the intensity of the banded spectrum.

Tables IV and V were obtained in the following manner. On a number of photographic plates the intensity of a strong band-line was

TABLE IV

Source of Light	Pressure: Current	Intensity of Band-Line 4928.8	Stationary Intensity of Series-Line $H\beta$
Negative glow.....	0.5 mm; 0.006 amp.	1	1
	0.1 0.01	1	5
	1.0 0.03	1	5
Positive column.....	40 0.05	1	3
	10 0.03	1	1
	0.1 0.003	1	1.5

TABLE V

Pressure, Cathode-Drop (Canal Rays)	Intensity of Band-Line 4634.15	Stat.-Intens. Series-Line $H\gamma$
0.5 mm; 2000 volts	1	3
0.05 2500	1	3
0.80 2500	1	4
*0.03 3000	1	3
*0.03 3000	1	3
0.05 4000	1	5
0.02 4200	1	3
0.01 4200	1	4
0.01 5000	1	3

compared with the stationary intensity of a neighboring series-line; the intensity of the band-line was called unity. The measures indicated by an asterisk in Table V refer to canal rays traveling away from the observer.

The relation here indicated between the intensity of the banded spectrum and the stationary portion of the series-line holds only for low temperatures; by raising the temperature one may, as shown below, create a displaced intensity which will mask the stationary intensity.

§ 12. *Correspondence between speed of translation and temperature; comparison of stationary and displaced intensities.*—From the existence of the Doppler effect in canal rays one may infer that the "carrier" of the line-spectrum is in motion while in the act of radiating light; and since the carrier, the positive ion, undergoes at the same instant both translation and radiation, one may suspect a connection between these two processes. The source of light in canal rays is evidently a diminution of the kinetic energy of these rays;

as we have already seen, § 5, the maximum speed of the canal rays is less than that computed from the cathode-drop; not only so, but this velocity becomes smaller the farther the canal rays proceed from the cathode.

As one might expect, and as A. S. King[1] has shown by experiment, it is possible to obtain the line-spectrum of a metal by increase of temperature alone. According to the kinetic theory of gases, a rise of temperature means an increase in the speed of translation of the gas particles, and the temperature is proportional to the mean square of the speed.

A purely thermal emission, or temperature radiation, of the line-spectrum and its emission from canal rays have this feature in common, that the carrier of the line-spectrum, the positive ion, has a motion of translation through a material medium and is simultaneously emitting electromagnetic waves. Temperature in the first case appears as the analogue of the square of the velocity of the canal rays in the second case.

The emission of light by canal rays is not a thermal or "regular" radiation, but a case of luminescence.[2] The difference between these two special cases, of the general principle or feature just mentioned, lies in the distribution of the radiating particles among the various values and the directions of the velocities.

In the case of thermal radiation the motions of the carriers lie in all possible directions, while in canal rays they all lie in a single direction. In the former case the total number of carriers is distributed among all speeds, from zero to very high values, according to the Maxwell-Boltzmann law. In the latter case the carriers are distributed, according to another law, among speeds ranging from zero to the maximum given by the cathode-drop.

From this it would appear, therefore, that there is an analogy, but no identity, in the laws governing these two types of emission. The stationary radiation is also a sort of luminescence between which and the displaced radiation no parallelism is to be expected such as that which exists between this latter and thermal radiation.

This is evident from Tables VI, VII, and VIII.

[1] *Annalen der Physik*, **16**, 360, 1905.

[2] E. Wiedemann, *Annalen der Physik*, **34**, 446, 1888; **37**, 177, 1889.

TABLE VI

Pressure, Cathode-Drop	Intensities	
	Band-Line 4205.2	Series-Line 3970.2 ($H\epsilon$)
0.05 mm; 2500 volts	1	3
0.02 3300	1	5
0.01 4600	1	5
0.005 7500	1	10
0.005 7500	1	10

TABLE VII

Pressure, Cathode-Drop	0.05 mm 2000 Volts		0.05 mm 2500 Volts		0.08 mm 2500 Volts		0.03 mm 3000 Volts		0.03 mm 3000 Volts		0.02 mm 4200 Volts		0.01 mm 4200 Volts		0.01 mm 5000 Volts	
Intensity	Stat.	Displ.	Stat.	Displ.	Stat.	Displ.	Stat.	Displ.	Stat.	Displ.	Stat.	Displ.	Stat.	Displ.	Stat.	Displ.
$H\beta$	..	..	1	4	..	..	..	..	..	..	1	4	1	6	1	4
$H\gamma$	1	3	1	3	1	5	1	6	1	6	1	5	1	8	1	5
$H\delta$	1	2	1	2	1	3	1	4	1	5	1	4	1	6	1	3
$H\epsilon$	1	1	1	1.5	1	1.5	1	3	1	3	1	2	1	2	1	2

TABLE VIII

Pressure, Cathode-Drop	2536.6 Intensity		3663.3 Intensity		4046.8 Intensity		4078.1 Intensity	
	Stat.	Displ.	Stat.	Displ.	Stat.	Displ.	Stat.	Displ.
0.05–0.01 mm ..... 3700–11100 volts	..	..	10	1	50	1	great	0
0.05–0.005 mm .... 6000–18000 volts	1	2	8	1	10	1	100	1
0.01–0.001 mm .... 16000–48000 volts	1	3	3	1	6	1	20	1
0.005–0.0005 mm .... 19000–57000 volts	..	..	2	1	5	1	4	1

The results of Table VI were obtained from grating spectrograms taken with the direction of observation perpendicular to that of the rays; the intensity here given for the series-lines is therefore the sum of the stationary and of the much greater displaced intensity. As will be seen, the displaced intensity of the series-lines is not proportional to the intensity of the banded spectrum, and hence not proportional to the stationary intensity of the series-lines.

Table VII was obtained from spectrograms on which the stationary and displaced intensities were separated by means of the Doppler effect, and could therefore be directly compared one with the other; for each separate line the stationary intensity is taken as unity. As will be seen, the distribution of intensity in the stationary spectrum follows a law different from that which governs the distribution in the displaced spectrum.

In Table VIII are the results from spectrograms of mercury vapor in which the stationary and displaced intensities were again separated by aid of the Doppler effect. Differing from hydrogen, the displaced intensity is here greater than the stationary only for the line $\lambda 2536$; in all other lines the reverse is true.

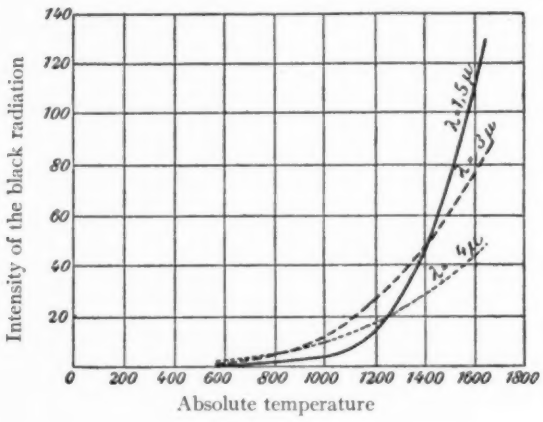


FIG. 11

A comparison of the three preceding tables shows that the displaced intensity does not behave like the stationary, becoming smaller as the number of collisions diminishes along with the gas-pressure. The displaced intensity appears rather to depend solely upon translational speed, with which it increases rapidly. This leads to the conjecture that the energy of the displaced intensity is transferred to the carrier of the radiation, not by collision, but from the kinetic energy of translation by means of radiation-pressure and during translation. The electron theory is confronted with the following question: Given a system of electrons in cyclic motion; suppose them so arranged that their total radiation is zero when the system is at rest with respect to the ether. Query: Will this neutral compensation between the radiations from the individual electrons still hold when the system has impressed upon it a translational velocity with respect to the ether?

§ 13. *Distribution of intensity, with Doppler effect.*—For the succeeding discussion let us make the following assumptions. The canal rays travel in parallel lines and experience no appreciable dispersion; the cathode-drop during exposure remains constant to within a few per cent. The distribution of the canal-ray ions among the different velocities is given by the broken curve in Figs. 12*a*–12*f*; squares of velocities are plotted as abscissae, and the number of canal-ray ions assigned to each velocity is given by the ordinates.

The intensity associated with any particular squared velocity (v^2) in the Doppler effect is proportional to the product of the number of particles (n) and the intensity of radiation (J) of the individual particle having the velocity in question, so that we have $E=n.J(v^2,\lambda)$. If J were independent of v^2—i. e., if $\delta J/\delta v^2=0$ then the distribution of intensity in the Doppler effect would be proportional to the velocity distribution ($E=kn$), since each of the n values would be multiplied by the same constant. We shall assume, therefore, that J is a function of v^2 in exactly the same manner that the black-body radiation (Fig. 11) is a function of the absolute temperature. The J,v^2-curve is that indicated by dotted lines in Figs. 12*a*–12*f*.

In Fig. 12*b* it is assumed that the intensity J increases with an increase of v^2 as indicated by the dotted curve. Since J is very small for small values of v^2, we find E also small, notwithstanding the fact that n is large. The displaced intensity falls off, therefore, with great rapidity in the region of small velocities; so that between the stationary and the appreciable, displaced intensity there lies a minimum of intensity.

In Figs. 12*c* and 12*d* it is assumed that, for two lines in the same series, the intensity J is a function of the wave-length λ; that, however, the intensities J_1 and J_2 vary in a constant ratio, giving us

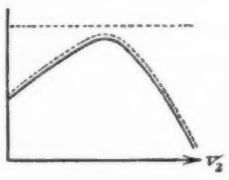
$$\frac{\delta J(\lambda_2)}{\delta v^2} : \frac{\delta J(\lambda_1)}{\delta v^2} = K .$$

In this case the total intensities in the Doppler effect, E_1 and E_2, would vary in the constant ratio K; the lines are similar; the widths of the intensity-minimum and the distances of the intensity-maximum from the stationary line are also equal.

In Figs 12*e* and 12*f* it is assumed that, for two lines of the same

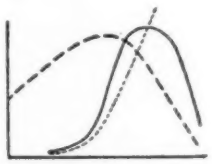
series, the intensity is a function of λ; that, however, the intensities do not vary in a constant ratio; accordingly

$$\frac{\delta J(\lambda_2)}{\delta v^2} = F(\lambda_1, \lambda_2, v^2)\frac{\delta J(\lambda_1)}{\delta v^2}.$$



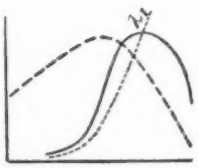
$$\frac{\partial J}{\partial v^2} = 0$$

Fig. 12*a*



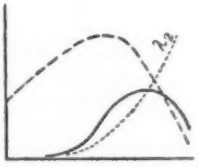
$$\frac{\partial J}{\partial v^2} > 0$$

Fig. 12*b*.



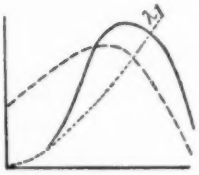
$$\frac{\partial J(\lambda_1)}{\partial v^2} = f(\lambda_1)$$

Fig. 12*c*



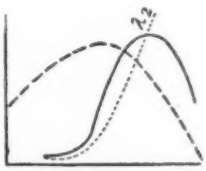
$$\frac{\partial J(\lambda_2)}{\partial v^2} = k\frac{\partial J(\lambda_1)}{\partial v^2}$$

Fig. 12*d*.



$$\frac{\partial J(\lambda_1)}{\partial v^2} = f(\lambda_1)$$

Fig. 12*e*



$$\frac{\partial J(\lambda_2)}{\partial v^2} = F(\lambda_1, \lambda_2, v^2)\frac{\partial J(\lambda_1)}{\partial v^2}$$

Fig. 12*f*

– – – – n = number of particles to v^2.
. . . . . J = intensity for n = constant.
——— E = intensity in Doppler effect.

In this case the distribution of the total intensities, E_1 and E_2, are no longer similar. If we assume that $\lambda_1 > \lambda_2$ and that

$$\frac{\delta J(\lambda_1)}{\delta v^2} < \frac{\delta J(\lambda_2)}{\delta v^2},$$

then the width of the intensity-minimum for λ_1 and the distance of the intensity-maximum from the stationary line are smaller than for λ_2. As the wave-length of the series-line diminishes, the width of the intensity-minimum, and likewise the distance of the intensity maximum, increase.

Before passing to experimental results concerning the distribution of intensity in the Doppler effect, the following sources of error should be distinctly recognized. It is not safe to compare with each other distributions of intensity in the Doppler effect for lines which do not have the same carrier. Nor is it admissible to compare with each other lines of the same series on different spectrograms; for it is impossible to produce two spectrograms under conditions which are exactly identical as regards cathode-drop, gas-pressure, and current-strength. The nv^2-curves of the two Doppler effects under comparison would not be identical in the two cases. The only reliable method is to compare the intensity-distribution of the Doppler effect for lines of the same carrier and upon the same spectrogram.

After this condition is satisfied, the problem is to compare distributions for lines of different intensities. Here errors are possible, owing to imperfections of the photographic method: the intensity, as measured by the blackening of the plate, may be underestimated in consequence of either over- or under-exposure. The results of § 15 and 16 are certainly subject to such errors. In order to secure some accuracy for the results of § 16, I have employed as many spectrograms as possible both of long and short exposure.

§ 14. *The intensity-minimum of the Doppler effect; condition necessary for its occurrence.*—We define the width of the intensity-minimum of the Doppler effect as the distance between the red and blue edges of the displaced band and the red and blue edges, respectively, of the stationary line, corresponding to positions *b* and *c*, respectively, of Fig. 4. If the intensity of the stationary line is great or the intensity of the displaced band small, then the photographic method yields too large a value for the width of the intensity-minimum. Indeed, an exact measurement of it is impossible; the numerical data concerning it have only a qualitative value.

This intensity-minimum is found in all series-lines of hydrogen, and in all lines of mercury and nitrogen. Among the spectrograms

now before me I fail to find it only in the second doublet of the principal series of potassium; this appears to be due partly to the fact that its width in this case is small, and partly to the fact that the dispersion of the spectrograph was too small.

The appearance of the intensity-minimum is to be explained not by the absence of the small velocities, but rather along the lines laid down in § 13, namely, that with small velocities the intensity of radiation from canal rays is small, just as with a low mean temperature the intensity of the purely thermal radiation is small. If, therefore, one wishes to demonstrate the existence of the Doppler effect with appreciable intensity for the lines of an element, he must work with canal rays of a maximum speed which is considerably greater than that corresponding to the width of the intensity-minimum. In Table IX are collected the widths of the intensity-minimum for some lines of the elements *K*, *H*, and *Hg*.

TABLE IX

Element	Wave-length	Width $\left(\frac{\Delta\lambda}{\lambda}\right)$ of Minimum	Necessary Cathode-Drop in Volts	Dependence of Intensity upon Temperature
K.....	4047.4 4044.3	very small, not measured	small	Found in Bunsen flame
H.....	4861.5	$8.4.10^{-5}$	229—687	May be produced in arc; not in Bunsen flame
Hg.....	2536.7	$2.3.10^{-5}$	2743—8229	Found in Bunsen flame
	4046.8	$3.7.10^{-5}$	2589—6767	Not in Bunsen flame; increases slowly with temperature
	4078.1	$6.1.10^{-5}$	5160—15480	Not in Bunsen flame; increases very rapidly with temperature

In the fourth column two values of the cathode-drop are given for each line; the smaller is computed from $\Delta\lambda$ and gives the actual velocity measured in volts; the second and larger value gives the drop which must be effective at the cathode in order to produce the observed velocity in the canal rays; according to § 5, the first value is from 1.5 to 3 times smaller than the second. If, for instance, one is working with mercury with a cathode-drop of less than 3000 volts, he will not find a trace of the Doppler effect at λ 4046; and at $\lambda\lambda$ 4078

and 5790, he will find, even with 10,000 volts, scarcely a trace of the Doppler effect and only the stationary line.

It appears from Table IX that the Doppler effect for any one of these lines appears for velocities which are smaller in proportion as temperature at which the line appears in purely thermal radiation is smaller. This is a result which might have been anticipated from what has been said in § 12 concerning the analogy between temperature and square of velocity in canal rays.

It is well known that observers have sought in vain for the Doppler effect in the positive column of the glow-discharge and in the electric arc. This negative result is a confirmation of the inference drawn above, namely, that there is associated with a small speed of translation only a low intensity of radiation. The potential-drop in the positive column is much smaller than at the cathode, and hence the ions there located acquire a relatively small speed in the direction of the current.

§ 15. *The distribution of intensity in a series-term.*—The three components (I, II, III) of the first subordinate series of mercury triplets are themselves compound, as indicated in Table X. For these I have tabulated the widths of the intensity-minimum in the grating spectrum of the first and second order. As will be seen, these widths are equal for all components of the series-term; and I have found the same to be true for the distance of the maximum intensity from the stationary line. Within a series-term, therefore, the distribution of intensity of the Doppler effect is the same for all components; according to § 13 the intensities of the components of a series-term vary in a constant ratio; this is independent of the square of the speed.

A comparison of the last two columns of Table X shows that within the series-term the ratio of the displaced to the stationary intensity is constant; the intensity of the line 2967 with which the others are compared is taken as unity.

It has been found by Küch and Retschinsky[1] that on varying the load (temperature, vapor-pressure) of a mercury lamp the lines 5461, 4359, and 4047 increase and decrease in a constant ratio. These three lines are the components of the first term of the second subordinate series of mercury. They find the same phenomenon in the

[1] *Annalen der Physik*, **20**, 563, 1906.

TABLE X

	Wave-Length	Width First Order	Width Second Order	Displaced Intensity	Stationary Intensity
I	3663.46	458	969	2	2
	3663.05				
	3655.00	429	921	3	3
	3650.31	...	949	10	10
II	3131.95	436	998	4	4
	3131.66				
	3125.78	432	995	3	3
III	2967.64	438	977	1	1
	2967.37				

case of the lines at λλ 6908, 6234, 5790, 4348, and 4078. We may therefore conclude that these lines represent the components of one and the same series-term (§ 6).

The preceding results suggest the following generalization and hypothesis. In any one term of a spectral series the distribution of intensity among the components is independent of the mode of excitation; but the absolute intensity of any component (and hence of all the other components), or the absolute intensity of the entire term, is a function of the mode of excitation (speed of canal rays, temperature). When viewed from an energy standpoint, or with reference to the amplitude of acceleration in the source of emission, the components of a series-term appear to be connected in some way in the ion.

It may be noted, in passing, that this relation between the components of a series-line may serve as a means for finding which lines *are* the components of any term.

§ 16. *Distribution of intensity in a series.*—In the second column of Table XI are given the reduced widths of the intensity-minimum of the Doppler effect for the series-lines $H\beta$, $H\gamma$, $H\delta$, $H\epsilon$, as observed on a grating spectrogram; in the third and fourth columns are collected the displaced and stationary intensities. We see that the width of the intensity-minimum increases as the wave-length diminishes through the series.

In Table XII are given the values of the squared velocities, as derived from a number of spectrograms, for which the intensity in the Doppler effect is a maximum for the series-lines $H\beta$, $H\gamma$, $H\delta$,

TABLE XI

Wave-Length	Breadth of Minimum $\frac{\Delta\lambda}{\lambda}$	Displaced Intensity	Stationary Intensity
$H\beta$ 4861.5	426	7	5
$H\gamma$ 4340.7	470	6	6
$H\delta$ 4101.8	492	3	3
$H\epsilon$ 3970.2	516	1	1

and $H\epsilon$. As will be observed, the intensity-maximum is associated with larger velocities as the wave-lengths diminishes. The three bracketed values for $H\epsilon$ appear to form an exception to this rule, probably because the measurement of $H\epsilon$ is rendered uncertain by a neighboring line not belonging to the series.

TABLE XII

SQUARE OF VELOCITY CORRESPONDING TO MAXIMUM INTENSITY
(Unit = 10^{14} cm^2/sec^2)

Wave-Length	1	2	3	4	5	6	7	8	9	10
$N\beta$ 4861.5	4.48	....	5.53	3.65	4.86	....	....	.....	.....	7.47
$H\gamma$ 4340.7	5.02	....	6.04	7.03	6.90	7.95	....	8.22	9.37	12.89
$H\delta$ 4101.8	....	5.58	....	7.24	7.35	9.24	8.15	8.46	12.00	12.92
$H\epsilon$ 39.702	....	5.59	....	....	....	[8.84]	9.13	[7.10]	12.33	[12.74]

When the direction of the canal rays and the direction of observation are at right angles, one obtains, as already indicated, the sum of the stationary and the displaced intensities. However, the latter is, in the case of hydrogen, considerably greater than the former; hence the error will not be large if one places the observed total intensity equal to the stationary (displaced?).

TABLE XIII

Wave-Length	Observed Cathode-Drop in Volts				
	2500	3300	4600	7500	7500
$H\beta$ 4861.5	24	24	18	24	24
$H\gamma$ 4340.7	12	12	12	32	36
$H\delta$ 4101.8	4	4	4	8	9
$H\epsilon$ 3970.2	2	2	2	2	3
$H\zeta$ 3889.1	1	1	1	1	1

TABLE XIV

Wave-Lengths	Observed Cathode-Drop in Volts					
	2000	3300	3500	5000	7500	7500
$H\beta$ 4861.5	20	24	26	24	27	27
$H\gamma$ 4340.7	16	30	36	36	54	54
$H\delta$ 4101.8	8	12	12	18	27	27
$H\epsilon$ 3970.2	4	4	4	6	9	9
$H\zeta$ 3889.1	2	2	2	3	3	3
$H\eta$ 3835.6	1	1	1	1	1	1

This has been done in Tables XIII and XIV, the former having been obtained from a grating spectrogram, the latter from a prism. In each of these tables the values of the displaced intensities are given for different values of the cathode-drop, the unit being the weakest line of the series, $H\zeta$ and $H\eta$ respectively; it is to be remembered that the sensitiveness of the photographic film in the $H\gamma$–$H\zeta$ region is somewhat variable, while at $H\beta$ it is considerably smaller than at $H\gamma$.

If one compares the intensity of distribution for various values of the cathode-drop, as observed on the electrometer, he is struck by two features which repeat themselves with regularity. First, in the hydrogen series—the intensity-maximum shifts toward the smaller wave-lengths as the velocity increases; and, secondly, the decrease of intensity, in the ultra-violet terms, just above the maximum, is steeper in proportion as the maximum moves toward the shorter wave-lengths.

The analogy between these two phenomena and the dependence of the intensity of black-body radiation upon temperature is at once evident. As is well known, and as may be seen at a glance from Fig. 13, the maximum of intensity of black-body radiation shifts in the direction from red to blue with rising temperature; and further the decrease of intensity on the side of the short wave-lengths, just above the maximum, becomes steeper as the maximum approaches the blue—i. e., as the temperature increases.

We may suppose that the line-spectrum emitted by the arc or by the condensed spark at atmospheric pressure is principally a thermal radiation. After finding the two characteristic features of intensity-distribution in a series which have been mentioned above, the follow-

ing question occurred to me. In the case of thermal radiation of a series of lines, does an analogous law hold for the distribution of intensity throughout the series? If so, and if the temperature of the condensed electric spark is higher than that of the arc, then we should expect the maximum of intensity for the series to lie nearer the blue in the case of the spark than in the case of the arc; not only so, but we should expect the blue side of the maximum to be steeper in the case of the spark than with the arc. So far as I have been able to test these conclusions, from the data concerning intensity which have been given in an incidental way by those who have measured wave-lengths, I find them verified. I will give merely the following example.

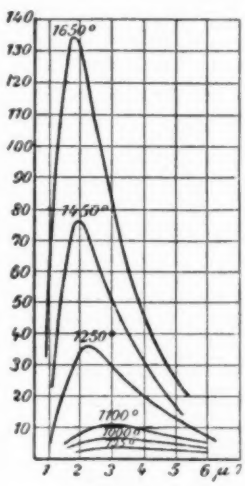


Fig. 13

The values for the intensity of arc-lines given in Tables XV–XIX are from Kayser and Runge; those for the intensity of the spark-lines in Tables XV, XVIII, and XIX from Eder and Valenta; and those in Tables XVI and XVII from Exner and Haschek. Tables XV and XVI contain doublets; Tables XVII, XVIII, and XIX, triplets. In Table XVIII the principal line of each series-term is indicated by an asterisk.

On comparison of the five following tables, one observes the following regularities. First, if the intensity-maximum lies within the series (Tables XV and XVII), it falls upon a shorter wave-length in the case of the spark than in the case of the arc. Secondly, the intensity of the series-terms just above the maximum falls off much more rapidly in the spark than in the arc.

Tables XVIII and XIX show also that the intensity-distribution in a series-term (§ 15) does not follow the above law for the intensity-distribution in the series. For instance, the second or third component of the mth term of a series may have a shorter wave-length and yet a greater intensity than the first component of $m+1$th term.

§ 17. *Widening of lines in a series by means of Doppler effect.*—In a gas which is made luminous by purely thermal means, and which is emitting a line-spectrum, the "carriers" of the radiation have their

velocities in all possible directions; in consequence of Doppler's principle the lines will therefore be widened on both sides. If the density of the luminous particles remains constant, this widening must increase with the temperature. These are inferences which have already been drawn by other observers. Our purpose here is merely to call attention to the bearing which the above results concerning the dependence of the intensity of radiation upon translational velocity has upon this type of widening.

TABLE XV

POTASSIUM, PRINCIPAL SERIES

WAVE-LENGTH	INTENSITY	
	Arc	Spark
7699	10	8
7666	10	8
4047.04	8	10
4044.3	8	10
3447.5	6	10
3446.5	8	
3217.8	4	2
3217.3	6	
3102.4	2	1
3102.2	4	
3034.9	4	..
2992.3	2	..
2963.4	1	..
2942.8	1	..

TABLE XVI

ALUMINUM, SECOND SUBORDINATE SERIES

WAVE-LENGTH	INTENSITY	
	Arc	Spark
3961.68	10	100
3944.16	10	50
2660.49	10	3
2652.56	10	2
2378.52	6	?
2373.45	.4	2
2263.52	8	1
2258.27	2	..
2204.73	4	..
2199.71	1	..

TABLE XVII

ZINC, SECOND SUBORDINATE SERIES

WAVE-LENGTH	INTENSITY	
	Arc	Spark
4810.71	10	?
4722.26	10	500
4680.38	10	300
3072.19	10	10
3035.93	10	5
3018.50	8	3
2712.60	7	2
2684.29	7	2
2670.67	6	..
2567.99	5	1
2542.53	5	..
2530.34	4	..
2493.67	4	..
2469.72	3	..
2457.72	2	..
2449.76	1	..
2427.05	1	..
2415.54	1	..

TABLE XVIII

MERCURY, FIRST SUBORDINATE SERIES

WAVE-LENGTH	INTENSITY	
	Arc	Spark
3663.46	5	9
3663.05		
3655.00	5	8
3650.31	10*	10*
3131.95	8	10
3131.66		
3125.78	10*	10*
2967.64	10*	10*
2967.37		
3027.66	2	..
3023.64	2	..
3021.68	4*	8*
2655.29	5	1
2653.89	5	1
2652.22	8*	4*
2536.12	10	10
2534.89	7*	7*
2803.69	4*	3*
2482.14	4*	1*
2378.40	5*	2*
2699.74	2*	..
2399.64	4*	..
2301.57	1*	..

TABLE XIX

MERCURY, SECOND SUBORDINATE SERIES

WAVE-LENGTH	INTENSITY	
	Arc	Spark
5460.97	10	10
4358.56	10	10
4046.78	5	10
3341.70	5	8
2893.67	5	10
2752.91	9	8
2925.51	8	3
2576.31	8	6
2464.15	5	4
2759.83	5	2
2446.96	5	1
2345.41	4	2
2675.20	1	..

At a distance $\Delta\lambda$ from a stationary line produced by thermal radiation one may observe an intensity which is due to a large number of carriers; all velocities greater than $c \times \Delta\lambda/\lambda$ may indeed contribute to this intensity. If the angle between the direction of the velocity and the direction of observation be denoted by a, then all particles for which

$$v \cos a = c \cdot \frac{\Delta\lambda}{\lambda}$$

will contribute to the intensity E at $\Delta\lambda$. Let n_i be the number of particles which have the speed v_i and have also the direction (a_i) prescribed by the preceding equation. Then, according to § 13, the total intensity becomes

$$E = n_1 \cdot J(\lambda, v_1^2) + n_2 \cdot J(\lambda, v_2^2) +, \text{ etc.}$$

It is at once clear that the widening, due to the Doppler effect in a line produced by thermal radiation, is a complicated function of the

temperature; and so long as the function $J\ (\lambda,v^2)$ is unknown this distribution of intensity cannot be computed.

According to § 15 we have for the components of any one term in a series

$$\frac{\delta J(\lambda_2)}{\delta v^2} : \frac{\delta J(\lambda_1)}{\delta v_2} = k\ .$$

This shows that these lines, widened by means of the Doppler effect, have the same distribution of intensity when the reduced measure, $\Delta\lambda/\lambda$ is employed.

But for the terms of a series this theorem does not hold. For according to § 16, we have for this case

$$\frac{\delta J(\lambda_2)}{\delta v^2} = F(\lambda_1, \lambda_2, v^2) \cdot \frac{\delta J(\lambda_1)}{\delta v^2}\ .$$

Hence the intensity-distribution in the reduced widening of the lines of two different terms in a series is not the same. The larger $\Delta\lambda/\lambda$ becomes, the greater is the intensity in the widened parts of the short wave-lengths as compared with the long wave-lengths. As the temperature rises, the broadening which is visible increases more rapidly for the blue than for the red terms of the series.

PART III. TRANSLATIONAL VELOCITY AND WAVE-LENGTH

§ 18. *Introduction, sources of error.*—As indicated above, the ions in the canal rays have a high speed and emit at the same time a line-spectrum whose intensity increases rapidly with the square of the velocity. Those amplitudes in the centers of emission (negative electrons) in the ion which are sufficient to emit light must therefore increase rapidly with the square of the translational velocity, and they must simultaneously experience in a direction opposite to that of their translation, a light-pressure whose value is proportional to the rapidly increasing intensity of radiation and to the velocity of translation. Both the increase in the amplitude of the centers of emission and the light-pressure will combine to produce a slight deformation of the "carrier" of the radiation, the positive ion. The question now arises as to whether this deformation will produce a perceptible change of wave-length.

This question may be replaced by another consideration which would appear to be valid when the system of electrons (positive ion) in translation emits no electromagnetic waves during the translation. Between the electrons of an ion (*Atomion*) there are doubtless electromagnetic forces at work. The variations of these quantities are propagated through the ether with the speed of light c; and if the sources of the electric lines of force, the electrons, have themselves a velocity v, there will result from the composition of these two velocities a modification of the electromagnetic forces between the electrons, which will be measured by the even powers of the ratio v/c. The question now is whether this modification of the electromagnetic forces in the ion will bring about an appreciable change in the wave-lengths emitted.

Since the variation of wave-length in question is a function of v^2/c^2, it ought to be possible to observe it by eliminating the Doppler effect—i. e., by placing the direction of observation at right angles to the direction of translation, hence normal to the direction of the canal rays. In a preliminary paper I have already described some observations of this kind made with a prism spectrograph; as the speed of the canal-rays increased, the wave-lengths emitted seemed to shift toward the red: in two instances $H\epsilon$ appeared to break up into two components; in every case the total radiation was polarized in such a way that the vibrations parallel to the direction of translation were a trifle stronger than those normal to this direction.

The experiment dealing with the polarization of light from canal rays I mean to take up again. The question concerning the displacement of the lines I have already investigated with the concave grating. The results are described below. But first let me state that, in my opinion, these results do not conclusively prove that the translation of a radiating particle produces a change of wave-length proportional to the square of the velocity. I am unable to say to just what extent the observations are affected by error.

It is possible, of course, that the observed displacement is partly due to the Doppler effect. In order to separate these two, the direction of observation—i. e., the line joining the slit and the center of the grating—must be exactly perpendicular to the beam of parallel canal rays. By the aid of a large iron square I have always taken

particular pains to make these two directions mutually perpendicular; in several cases I left this part of the adjustment to Messrs. Kinoshita and Siegel. In spite of this care, and notwithstanding the fact that in every case the displacement was toward the red end, it is possible we have systematically placed these two directions out of plumb; in any event, it is not possible to make any definite statement concerning the amount of the error. In one case where the cathode-drop was 7500 volts the displacement of the middle of $H\gamma$ was 0.42 Å. U. toward the red. To produce such a shift by means of the Doppler effect with a maximum velocity of 0.5×7500 volts (or 8.38×10^7 cm sec.) would require that the canal rays move away from the slit at an angle of 91° 59′, the error in adjustment thus amounting to 1° 59′.

It is possible, too, that my observations and results are affected by still other errors. Since the experiments are new, and since definite experimental evidence of shift of the lines toward the red would be a matter of great import, my observations may be fairly received with a certain amount of mistrust. However, I here state them in order that the reader may form his own judgment as to what has been obtained by the means at my disposal, and in order that this may possibly lead to more reliable investigations.

§ 19. *Widening of lines when directions of observation and translation are at right angles.*—In Table XX are given the widths of the lines $H\beta$, $H\gamma$, and $H\delta$ as they appear in the negative glow and in canal rays for different values of cathode-drop. In the first half of each double column the value of the line is given in terms of $_2{}^1{}_0$ mm; in the second half the value is given in terms of $H\delta$ as a unit. It will be observed that in general the width of each line increases with the speed of translation, $H\delta$ widening more rapidly than $H\gamma$, and $H\gamma$ more rapidly than $H\beta$.

TABLE XX

WIDTH OF LINES AT DIFFERENT CATHODE-DROPS (VOLTS)

(Unit = $_2{}^1{}_0$ mm)

Line	Neg. Glow		2500 Volts		3400 Volts		4200 Volts		7500 Volts		8000 Volts	
$H\beta$...	13.53	2.76	19.33	2.21	20.20	2.12	18.93	1.94	21.23	1.93	28.80	1.76
$H\gamma$...	6.75	1.38	15.23	1.74	15.27	1.60	13.76	1.41	19.33	1.40	25.23	1.54
$H\delta$...	4.90	1	8.76	1	9.53	1	9.76	1	11.00	1	16.33	1

The aperture of the grating used was 8.6 cm, the distance of the slit from the center of the grating being 100 cm. Those canal rays which sent light just to the edge of the grating would furnish rays of light to the observer under an angle of $2° 27'$ with the axis of the grating. From this would result a widening of the line by Doppler's principle. In the second column of Table XXI are given the values of these widths computed on the assumption that the actual speed is 50 per cent. of that which one would expect from the cathode-drop. The third column contains the observed values computed in Ångström units from Table XX.

TABLE XXI

Cathode-Drop in Volts	Width of $H\gamma$ in Å. U.	
	Computed	Observed
2500	0.60	1.24
3400	0.70	1.25
4200	0.77	1.12
7500	1.04	1.58
8000	1.07	2.06

§ 20. *Displacement of middle of line toward red.*—By the aid of a Zeiss comparator, I measured the distance of the following lines from $H\beta$, several times on each grating spectrogram, namely, several band-lines [2), 3), 4), 7)], two mercury lines [5) = 4358, 8) = 4047], and the line $H\gamma$. Table XXII gives three examples of such measurements. In the first part of each principal column is given the mean of three series of measures; besides this the mean error is also stated. Those columns which are headed "reduced" contain values computed as follows. Under the conditions employed it seems probable that the band-lines and the mercury lines in the canal rays suffer no displacement; accordingly the spectrograms of the canal rays were reduced to those of the negative glow as appears from Table XXII. For each spectrogram the following differences were computed:

8)−7), 8)−5), 8)−4), 8)−3), 8)−2), 7)−5), 7)−4), 7)−3), 7)−2), 5)−4), 5)−3), 5)−2), 4)−3), 4)−2), 3)−2)

Then the quotient of each difference for the negative glow by the homologous difference for the canal rays was taken; the mean of all

TABLE XXII

Line	Neg. Glow		Canal Rays 4200 Volts			Canal Rays 7500 Volts		
		Mean Error	Dist. of $H\beta$		Mean Error	Dist. of $H\beta$		Mean Error
			Obs.	Reduced		Obs.	Reduced	
1) $H\beta$	.....	....	.....	.....	....	.....	.....	....
2)	13958.7	0.66	14013.3	14015.1	3.32	13994.3	14001.3	1.60
3)	22327.3	0.88	22371.7	22374.6	3.27	22351.0	22362.1	2.18
4)	27585.0	3.70	27651.3	27654.9	4.03	... ...	.....	....
5) Hg ..	30910.3	2.85	30967.3	30971.3	3.27	30957.7	30973.2	2.05
6) $H\gamma$ ..	32005.3	0.66	32048.3	32073.5	2.44	32062.0	32078.0	0.13
7)	40312.0	3.21	40355.0	40360.2	3.87	40325.7	40345.8	2.72
8) Hg ..	50024.3	2.96	50079.7	50086.2	3.91	.....	.....	....

these quotients gave the reduction-factor for the spectrogram of the canal rays; the "reduced" distances were obtained by multiplying all the observed distances on any one spectrogram by its reduction-factor. In those plates taken with 4200 volts, the reduction-factor was 1.00013; with 7500 volts it was 1.00050. After the reduction of the spectrograms, the following differences were computed:

$$2)_k - 2)_g,\ 3)_k - 3)_g,\ 4)_k - 4)_g,\ 5)_k - 5)_g,\ 7)_k - 7)_g,\ 8)_k - 8)_g$$

where the subscripts $_k$ and $_g$ refer to spectrograms of canal rays and glow discharge, respectively. The mean of these differences is the displacement of the middle of the line $H\beta$ in the canal rays with respect to the middle of the same line in the negative glow. Besides these the following differences were computed.

$$[6)-2)]_g - [6)-2)]_k,\quad [6)-3)]_g - [6)-3)]_k,\quad [6)-4)]_g - [6)-4)]_k,$$
$$[6)-5)]_g - [6)-5)]_k,\quad [7)-6)]_k - [7)-6)]_g,\quad [8)-6)]_k - [8)-6)]_g.$$

The mean of these differences is the displacement of the middle of the line $H\gamma$ in the canal rays with respect to the same line in the negative glow.

TABLE XXIII

Cathode-Drop in Volts	Displacement toward Red in Ångström Units	
	$H\beta$	$H\gamma$
4200.....	0.93	0.17
7500.....	0.71	0.42

Table XXIII contains the displacement of $H\beta$ and $H\gamma$ computed in this manner for cathode-drops of 4200 and 7500 volts.

§ 21. *Displacement of series-lines by rise of temperature.*—In the second part of this paper we have discussed the far-reaching analogy between speed of translation and intensity of radiation for canal rays, on the one hand, and temperature and intensity of thermal radiation, on the other hand. If the displacements observed above have not been produced by the Doppler effect, but are really a function of v^2/c^2, we may draw the following conclusion from the analogy just stated: Lines emitted by a gas made luminous by thermal means, when compared with stationary lines, such as those of the negative glow, should be displaced toward the red in proportion as the temperature of the luminous gas is increased.

It has been certainly proved[1] by Jewell, Humphreys, Mohler, and Ames that the lines of the arc-spectrum are slightly shifted toward the red as the pressure about the arc is increased. My own experience, and the results of Küch and Retschinsky[2] with the mercury arc, leave no doubt that along the axis of the arc the temperature rises with the potential-drop and with the energy used per cubic centimeter; on the other hand, when the pressure is constant, the temperature varies only slowly with the current-strength; for, in this case, it is only the cross-section of the arc and not the energy per unit volume that increases.

Ames and Humphreys[3] report that the difference of wave-length, for the D lines, between the Bunsen flame and the arc does not exceed 0.002 Å. U. Now, the temperature at the center of the arc is very considerably higher than that of the Bunsen flame; however, its value falls off rapidly from the axis to the outer layers of the arc. For any one line, therefore, the observed intensity is made up of components from different layers of the arc, each at a high temperature. If the line is found in the layers of low temperature—i. e., the outside layers—then the radiation from the inner layers will be absorbed by the outer layers, and the observed intensity will be principally that of the outer, not that of the inner and more highly heated, layer.

Thus the lines actually observed in the principal and two subordinate series may have their origin in one and the same arc, at the same

[1] Kayser, *Handbuch der Specktroskopie*, **2**, 322, 1902.

[2] *Annalen der Physik*, **20**, 563, 1906. [3] *Phil. Mag.*, **44**, 119, 1897.

pressure, but at different temperatures. The above-mentioned investigators found that in the three series the pressure-shift was in the ratio 1:2:4.

Still another inference is to be drawn. According to § 16 the radiation-temperature for a series of lines is higher in the spark than in the arc. If, therefore, the influence of temperature upon wave-length is that which is here imagined, the spark-lines should be slightly displaced toward the red when compared with the arc lines. As to whether this is the case, there appears as yet no agreement[1] between observers who have studied the question, namely, Exner and Haschek, Kayser, Eder and Valenta, and Kent.

My thanks are due to Professor Riecke, who has throughout this work been cordial in his support and has placed at my disposal the necessary apparatus. I wish also to thank Professor Runge for kindly loaning me his short-focus concave grating.

[1] Kayser, *Handbuch der Spectroskopie*, **2**, 308; *Zeitschrift für wissenschaftliche Photographie*, **3**, 308, 1905.

THE CHARACTER OF THE STAR IMAGE IN SPECTROGRAPHIC WORK

By J. S. PLASKETT

The object of this paper is to describe some experiments on the size and form of the star image given by the combination of objective and correcting-lens, with an investigation into the causes of the observed effects and suggestions for the improvement of existing conditions.

The equipment of the Dominion Observatory, Ottawa, for radial-velocity work consists of a 15-inch telescope with a Brashear visual objective and photographic correcting-lens, and a spectroscope of the universal type, also by Brashear. The objective for visual purposes is excellent, and the spectroscope is admirably adapted for general spectroscopic work, but, as the experience of others as well as myself has shown, is not suitable for the accurate determination of radial velocities. Its design as a universal spectroscope does not give sufficient stability, and, in exposures of any length, flexure will not only ruin the definition, but is liable to introduce systematic errors in the velocities obtained. Pending the construction of a spectrograph specially designed for the required purpose, an attempt was made to render the present instrument capable of giving accurate velocity values. The investigation and removal of the known sources of error led to the discovery of the aberrations to be presently described. A brief description of the steps leading thereto may be of interest.

Trusses connecting the various parts of the instrument, where flexure could occur, with the supporting tubes were applied to such effect that an initial displacement of the spectral lines, equivalent to a velocity of 30 km per second, occasioned by a movement of telescope and spectroscope through two hours in right ascension, was reduced to 1½ km. The prisms were firmly clamped in place, without inducing strains in the glass, by screws passing through the base of the prism-box and the minimum-deviation linkwork into the prism-cells. The slit-jaws, originally too thick on the edge, were reground,

and the occulting diaphragms for star and spark light were removed from the slit-head and placed on an independent frame attached to the supporting tubes. The comparison apparatus was remodeled, the direction of the spark being made transverse to, instead of parallel with, the slit-jaws, and many other smaller details were carefully attended to.

After all known sources of error in the spectroscope itself had been overcome, and after it had been placed in thorough adjustment, it was found that test spectra of the standard-velocity stars occasionally gave values differing by as much as 3 km per second from those obtained by other observers. As the probable error of the mean of the measured lines did not exceed four-tenths of a kilometer, and as all the other known causes of systematic error had been overcome, it seemed probable that this might be due to unsymmetrical distribution of the star light over the collimator and camera lenses. Evidently such unsymmetrical distribution can cause a displacement of the lines only when the camera is not in exact focus. The camera was always carefully focused by a modification of Newall's method, which readily detected displacements of the sensitive surface from the focal plane of less than 0.05 mm in a focal length of 375 mm. But as the plates are supported only at the ends of the plate-holders, differences in the curvature of the glass may easily cause differences of 0.1 mm or more in the position of the center of the sensitive surface, where all measurements are made. In the case of a displacement of 0.1 mm from the focus, a distribution of the star light on the collimator objective so that its center of intensity is 5 mm to one side of the axis, is sufficient to cause a displacement of the spectral line $\frac{5}{375} \times \frac{1}{10} = \frac{1}{750}$ mm equivalent to a velocity of 1.8 km per second.

An examination of the illumination pattern on the collimator lens, both visual and photographic showed how easily such or even greater displacements of the center of intensity could occur even with the utmost care in guiding. The illumination could never be made uniform, no matter how the relative positions of slit and correcting-lens were altered. The pattern was either a diametrical bar parallel to the slit of a width about one-third or one-fourth the aperture, or else such a bar with the addition of a peripheral ring; while a very slight movement of the slit-jaws to one side or other was sufficient to cause

one side only of the lens to be illuminated, without causing any appreciable change in the appearance of the image in the guiding telescope, guiding being done by means of light coming through the slit. It is easy to see how the center of intensity of the star light could be displaced without the observer being aware of the fact, thus causing a displacement of the star lines unless the plate were in exact focus.

The appearance of this pattern and its behavior for change of slit position indicated spherical aberration of the condensing system. That aberrations of some nature were present was indicated not only by the long exposures required—upward of two hours for a star of the fourth photographic magnitude—but also by the large effective diameter of the image as shown by the wide opening, 0.25 mm, of the slit required to obtain uniform illumination.

An examination of the correcting-lens showed that part of the difficulty might arise from the accidental inversion of the diverging element, which had been so placed in the cell that surfaces of unlike curvature were adjacent to each other. On inverting this concave element so that surfaces of like radius of curvature were in contact, the illumination pattern became more uniform, the required exposure time was diminished by 50 per cent. and no errors of a greater magnitude than should be expected with the dispersion employed, appeared in velocity determinations of standard stars. If the diameter of the object-glass, 15 inches, and the linear dispersion of the spectrograph, 18.6 tenth-meters per millimeter at $H\gamma$, be taken into account, the exposures required—less than an hour for stars of the fourth photographic magnitude—compare very favorably with those of other equipments.

Notwithstanding the great improvement shown, photographic tests of the star focus for different temperatures indicated that the star spectrum was much wider than could reasonably be accounted for by atmospheric disturbance, and I was led to make thorough tests of the character and diameter of the image.

To determine whether a narrower spectrum could be obtained by a change in adjustment, a plate was made for each of six settings of the correcting-lens, above and below its computed position, over a range of four inches. A simple device applied to one of the plate-

holders enabled ten successive star spectra to be made side by side on each of these plates, at different settings of the slit position in the neighborhood of the star focus; the sixty spectra forming a record of the diameter of the star image under varying conditions. To insure that the spectrum had not been widened by a drift of the star image along the slit, the spectroscope was turned in position angle until the slit-jaws were parallel to an hour circle. By opening the slit 0.2 mm, and by using a bright star, *Vega*, a fully exposed linear spectrum was obtained in eight or ten seconds, evidently with no chance of widening due to drift. The width of the narrowest part of the narrowest spectrum on each plate, presumably where the star was in focus on the slit, was measured, and these widths ranged from 0.085 to 0.115 mm. As the camera and collimator objectives are of the same focal length, and as one second of arc in the focus of the refractor is equivalent to 0.0275 mm, the diameter of the star image according to this test must be between 3″ and 4″.5. The diameter of the central diffraction disk as given by the formula $d=\frac{1.2197\lambda}{r}$ is, for a 15-inch objective and $H\gamma$ light, about 0″.57, while the actual effective diameter as obtained from the width of star spectra is five to eight times as great.

This enlargement of the diffraction image may be due to three causes: (1) aberrations in the spectroscope; (2) atmospheric disturbances; (3) aberrations in the system of objective and correcting-lens.

1. *Aberrations in the spectroscope.*—It is a simple matter to determine whether the wide star spectra obtained are due to this cause, for by direct photography of the star image no aberrations in the spectroscope can affect the result. A series of star trails was therefore made on ordinary plates by the system of objective and correcting-lens. A small plate, held in guides in the slit-cap of the spectroscope, could be moved in these guides between exposures so as to make a number of trails on each plate. The collimator tube, carrying the plate with it, was moved by the rack and pinion about a quarter of a millimeter between each exposure, to insure having one of the trails within an eighth millimeter of the focus. A plate each was made of six stars ranging from the third to the sixth magnitude, and the width of the narrowest trail on each plate, corresponding to the

position where the star was most nearly in focus, was measured. Although the conditions of seeing both for trails and spectra were above the average, about 3 in a scale of 5, the trails were not continuous but broken and jagged, owing to atmospheric disturbances, and the measurements were made in two ways: first, of the width of narrow short parts of the trails where the seeing had been momentarily steady; and, second, of the average width of a longer strip of trail. In the first series of measurements the widths varied from 0.070 mm in the fainter stars to 0.110 mm in the brighter stars, while the average widths of longer strips were about 20 per cent. greater. Since the widths of spectra were practically the same, it is evident that the cause must be sought in the star image itself, and is not due to aberrations in the spectroscope.

2. *Atmospheric disturbances.*—Newall in his paper on the design of spectrographs[1] has introduced a very useful conception, that of tremor-disks, and he states that atmospheric disturbances enlarge the effective diameter of the star image. Such enlargement may be due either to bodily displacements of the image from its mean position or to the spreading-out of the central image into a more or less expanded disk. He considers that the actual effect, so far as getting light through the slit of a spectrograph is concerned, is the same as if the image consisted of a central core from 1″ to 2″ in diameter surrounded by a more or less diffuse and gradually diminishing portion, the whole diameter being in the neighborhood of 4″ or 5″. If we accept Newall's estimates as correct, and if we remember that in no case was a sufficiently long exposure given to allow the outlying parts of the tremor-disk to increase the width of spectrum or trail, then the diameter of the image given by the Ottawa objective and correcting-lens, even allowing the extreme limit assigned by Newall for atmospheric disturbances, is nearly twice as great as it should be.

It is also a simple matter to test this conclusion experimentally. As the objective gives excellent visual definition, it may be safely assumed that the visual star image is of normal diameter. A measurement of the width of spectra and trails produced by the visual image, and a comparison with the widths given by objective and correcting-lens in photographic light, should at once decide whether the observed

[1] *Monthly Notices*, **65**, 808, 1905.

effect is due to atmospheric tremor. The correcting-lens was therefore removed, the spectroscope was adjusted for yellow light, and spectra were made similarly to the previous ones, though on Cramer Isochromatic plates, which have a pronounced band of sensitiveness almost identical in wave-length with the turning-point of the color-curve of the objective. The widths of the spectra produced varied between 0.050 and 0.065 mm, about 2″, but as the seeing was very unsteady (about 1½ in scale of 5), these widths are doubtless about 25 per cent. greater than would be the case with good seeing. For the star trails the same make of plate was used, light of shorter wave-length than λ 5000 being absorbed by a yellow screen of plane glass placed in contact with the plate. Owing to the insensitiveness of the plate to light of wave-lengths between λ 5000 and λ 5400, and to longer waves than λ 5800, only the light which is effective in forming the visual image can act in producing the trails. As before, the width of the trails varied with the brightness of the stars, ranging from 0.025 mm in faint trails to 0.055 mm in stronger trails, or from 1″ to 2″, while the average width over a longer strip of trail was about 20 per cent. greater. Notwithstanding the bad seeing, both trails and spectra were much more sharply defined than those made with the correcting-lens in photographic light and of only half the width.

These experiments conclusively prove that the abnormal width of spectra and trails in photographic light is not due to aberrations in the spectroscope nor to atmospheric disturbances, and clearly point to aberrations in the condensing system as the cause of the observed effects. A short summary of the experimental data will render this more evident. The theoretical diameter of the central disk, or rather of the first dark ring, for visual light λ 5600, is 0″.74, for photographic light, λ 4340, is 0″.57. The actual width of visual spectra and trails is from 1″ to 2″, or one and one-half to three times the theoretical diameter. The actual width of photographic spectra and trails is from 3″ to 4″.5, or five to eight times the theoretical diameter.

Some further information regarding the size and character of the photographic image may be gained by considering its effective diameter under another aspect, that of the loss of light at the slit. Referring again to Newall's paper, and taking, as he does for an example, a tremor-disk of 5″ diameter with a core of 2″, we find that

a slit 0.025 mm wide will transmit 31 per cent. of the incident star light; a slit 0.037 mm, 44 per cent.; a slit 0.05 mm, 58 per cent.; and so on. I am indebted to a suggestion by Professor Campbell for a method of testing this theoretical result experimentally. A series of star spectra were made at different slit-widths, and the resulting intensities were compared. As it is practically impossible to make a number of wide spectra of uniform intensity throughout their width, photometric measurements cannot be relied upon and recourse must be had to visual estimates. Such estimates can be made more accurately if the exposures are so regulated as to give spectra of equal intensity, and, moreover, within the limits of exposure time and intensity used here, errors due to the characteristics of the plate employed are to a great extent avoided. The spectrum of *a Lyrae*, the star used, is practically continuous except for the *H* series, and is therefore well suited for the estimation of intensities, while its brightness is such that only short exposures are required. Ten different slit-widths between 0.012 and 0.25 mm were used, and ten spectra, one through each slit-opening, were made side by side on the same plate. The exposures were so regulated as to render the resulting spectra as nearly equally intense as possible, and the final estimate is the mean from a number of plates and from spectra of different widths. To render the comparisons more direct, slit-widths will be represented by divisions, a single division corresponding to 0.025 mm, and the relative exposure times will be reduced to a unit of 100 with a slit-width of one division, 0.025 mm, or $0^{s}.91$, the normal width with the dispersion employed here.

The following table shows that the exposure required is inversely proportional to the slit-width until this reaches 0.1 mm, leaving out of account widths less than a single division, where diffractional loss within the collimator plays an important part. It also shows that with normal slit-width less than 17 per cent. of the light incident on the slit is transmitted. In Newall's hypothetical case 31 per cent. would be transmitted. The experimental data given above, using Newall's method of calculation, indicate a tremor-disk 8″ or 10″ in diameter with a core of about $3^{s}.5$, and, as the previous experiments have shown, this is much larger than can be accounted for by atmospheric disturbances.

TABLE I

LOSS OF LIGHT AT SLIT

SLIT-WIDTHS			COMPARATIVE TIMES FOR EQUAL INTENSITY	
Divs.	Mm	Secs.	Experimental	Computed: $\tau = 5'' \gamma = 2'$
½	0.012	0.45	300	
1	.025	0.91	100	100
1½	.037	1.35	67	70
2	.050	1.82	50	54
3	.075	2.73	33	39
4	.100	3.64	28	34
5	.125	4.55	25	31
6	.150	5.45	21.7	31
8	.200	7.27	18.3	31
10	.250	9.07	16.7	31

The above experiments point conclusively to aberrations in the system of objective and correcting-lens, when used with photographic light, as the cause of the observed effects, but they give no information concerning the nature of these aberrations beyond indicating in a general way, from the appearance of out-of-focus photographs of spectra and trails, that spherical aberration is present. It was decided therefore, to make quantitative tests to ascertain if possible the nature and magnitude of the aberrations and the best means of removing them.

The most simple and accurate method of determining the zonal errors and axial astigmatism of a telescope objective is Hartmann's method[1] of extra-focal measurements. The principle of the method and the measurements and reductions necessary are extremely simple, while it gives accurate values with the expenditure of comparatively little time and without the use of any appliances except such as can be readily made by anyone. For the benefit of those who have not the above paper at hand, and in order to render the present article complete, the essential principles of the method will be briefly described.

It depends upon the determination of the intersecting point of pencils of light coming from different parts of the objective. Suppose a diaphragm containing two small openings, equidistant from the

[1] *Zeitschrift für Instrumentenkunde*, **24**, 1, 33, 97, 1904.

center and along a diameter, be placed over the objective. If the distance between the pencils of light coming from these openings be measured at two points, one within and one without the focus, the point of intersection of the pencils, and consequently the focus for the particular zone in question, can be at once obtained from similar

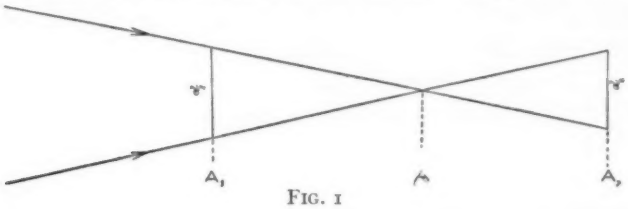


FIG. 1

triangles. For let d_1, Fig. 1, be the distance between the pencils at the scale-reading A_1 within the focus, d_2 the distance at the scale-reading A_2 beyond the focus. Evidently then the scale-reading for the focus A is $A_1+\left(\frac{d_1}{d_1+d_2}\right)(A_2-A_1)$. The distances d_1 and d_2 may be determined directly by micrometer measurements on the pencils from a star or distant artificial point-source, or by making exposures on photographic plates in the two positions and measuring the distances between the resulting images by a measuring microscope. The latter method is preferable and was used exclusively, except that the photographic determinations were checked by micrometer measures.

A zone plate *A*, Fig. 2, similar to that described by Hartmann, was employed. The apertures, except the four inner ones, were

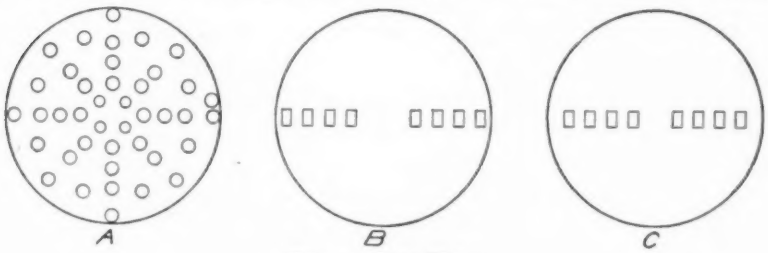


FIG. 2.—Zone Plates

each about 25 mm in diameter, and the radii of the nine zones were respectively 28, 47, 66, 85, 104, 123, 142, 160, and 178 mm. In order to determine the astigmatism along the axis, each pair of open-

ings is duplicated by a second similar pair at right angles, so that the focus of each zone of the objective is determined for two elements perpendicular to each other. In the case of the zone of 142 mm radius the focus can be obtained for four elements 45° apart. Thus an exposure within the focus, and a second one without the focus, give data sufficient to determine the focus of each of nine zones of the objective in two directions perpendicular to each other. These two directions are distinguished from one another in the measurement by making an extra aperture in the zone plate, which, on being reproduced in the negatives, serves to identify the origin and direction of the angle ϕ.

To determine the zonal errors of objective and correcting-lens, the zone plate was placed in position in front of the objective and a small photographic plate was placed in the guides in the slit-cap of the spectroscope. The spectroscope is supported on two parallel tubes carried by an adapter on the eye-end of the telescope, and can be readily moved up and down through a range of about 20 cm. Experience showed that the images were most sharply defined, and the best measurements could be obtained when the plates were between 6 and 10 cm from the focus. As the photographic focus was to be tested, an ordinary Seed 27 plate was first tried; but it was not found possible to make very accurate settings, as the pencils from the zone plate were spread out into radial spectra owing to the long range of wave-length (λ 5000 to the limit passed by the object-glass, say λ 3600) to which such a plate is sensitive. Several means of overcoming this difficulty were tried. As a yellow screen in front of an ordinary plate did not improve matters, the dispersion of the pencils must evidently be chiefly due to the light around $H\beta$. An ordinary lantern plate, which is sensitive from about λ 4600 down, was therefore next tried, and gave good images capable of accurate measurement; while if a yellow screen were used with such a plate the resultant images were again elongated, showing that the prolonged exposure entailed thereby had extended the action on the plate toward the red and reintroduced the first difficulty. A yellow or red star was used in preference to a white or blue, as limiting the action in the violet, shortening the effective range of spectrum, and thus giving images with less spectral dispersion and with no apparent elongation.

Four sets of extra-focal plates were made which, on being measured, reduced, and averaged, gave the focal positions of the nine zones as tabulated below (Table II). All four measures are in substantial agreement, which of course is closer for the outer zones where the convergency of the pencils is greater. There the probable error of a single determination of the focus does not exceed 0.1 mm, while near the center it may be as great as 0.5 mm. It will be noticed that the focus for the edge of the objective and correcting-lens is upward of 2 mm longer than the focus near the center, and if astigmatism be taken into account also, the difference is greater than 2.5 mm. The values are plotted graphically in the curve (*A*) of Fig. 3, the vertical distances being magnified some six or seven times, the appended scale representing millimeters. The horizontal line is drawn in the position of focus 75.34 that gives the smallest circles of confusion, in this case 0.04 mm in diameter. The astigmatism will increase this to some extent, so that probably the diameter will be nearly 2″. Unless the slit is set exactly at this mean position, which is not likely, the diameter of the confusion disks will be still further increased, so that we may consider 2″ as a moderate estimate. It must be remembered, however, that in speaking of circles of confusion the conceptions of geometrical optics alone are being considered, and no account is taken of diffraction phenomena, which may have some effect on the geometrically calculated dimensions of the star disk resulting from aberrations of the magnitude here present. However, the experiments on the width of spectra and trails showed conclusively that the photographic image was about 2″ greater in diameter than the visual image, presumably unaffected by aberrations, and this agrees with the geometrical theory.

To determine where the aberrations arise it is necessary to accurately compare the performance of the objective used visually with the performance of the objective and correcting-lens in the photographic part of the spectrum. Zonal tests were therefore made of the objective alone. For this purpose the wave-length of the light used must be limited to λ 5400–λ 5800, the range to which the eye is most sensitive, which is the most luminous in the spectrum, and which coincides with the turning-point of the color-curve of the objective. Fortunately, as the band of color-sensitiveness of Cramer Isochro-

TABLE II

ZONAL FOCI OF 15-INCH OBJECTIVE

RADIUS OF ZONE	ϕ	OBJECTIVE AND CORRECTING-LENS PHOTOGRAPHIC			OBJECTIVE ALONE VISUAL		
		Focus	Mean	Astigmatism	Focus	Mean	Astigmatism
28	45°	73.54		−0.20	106.43		−0.05
	135	73.94	73.74	+ .20	106.54	106.48	+ .06
47	0	74.19		+ .08	108.35		+ .42
	90	74.03	74.11	− .08	107.51	107.93	− .42
66	45	73.54		− .30	106.67		− .13
	135	74.14	73.84	+ .30	106.93	106.80	+ .13
85	0	74.15		+ .11	106.42		+ .26
	90	73.94	74.04	− .10	105.91	106.16	− .25
104	45	74.65		− .23	106.15		− .08
	135	75.11	74.88	+ .23	106.31	106.23	+ .08
123	0	75.68		+ .22	106.20		+ .09
	90	75.25	75.46	− .21	106.02	106.11	− .09
142	22.5	75.93		+ .24	106.08		+ .20
	67.5	75.32		− .37	105.77		− .11
	112.5	75.67		− .02	105.82		− .06
	157.5	75.83	75.69	+ .14	105.83	105.88	− .05
160	45	75.58		− .15	105.91		+ .04
	135	75.88	75.73	+ .15	105.83	105.87	− .04
178	0	76.11		+ .21	105.93		− .01
	180°	75.69	75.90	− .21	105.95	105.94	+ .01
Mean focus		75.34			106.01		

matic plates almost exactly coincides with the same region, all that is necessary in order to obtain photographic test plates is to absorb the blue and violet light by a suitable screen, and thus confine the action to the visual part of the spectrum. A deep yellow screen with plane parallel surfaces was used in contact with the plate. Although the pencils from the zone plate are displaced slightly on passing through this screen, these displacements are proportional, and the only effect will be to lengthen the focus for all the zones by the same amount, about one-third the thickness of the screen, without in the least altering the relative positions of the pencils. An exposure of about a minute on *Capella*, through the screen, with the plate from 60 to 100 mm from the focus, gives a negative of good intensity in which the images of the pencils are quite round and free from any noticeable spectral elongation, thus allowing accurate measurement.

Five sets of extra-focal exposures were made in the visual part of the spectrum, and the mean values resulting from the measurement and reduction of these plates are given in Table II and plotted graphi-

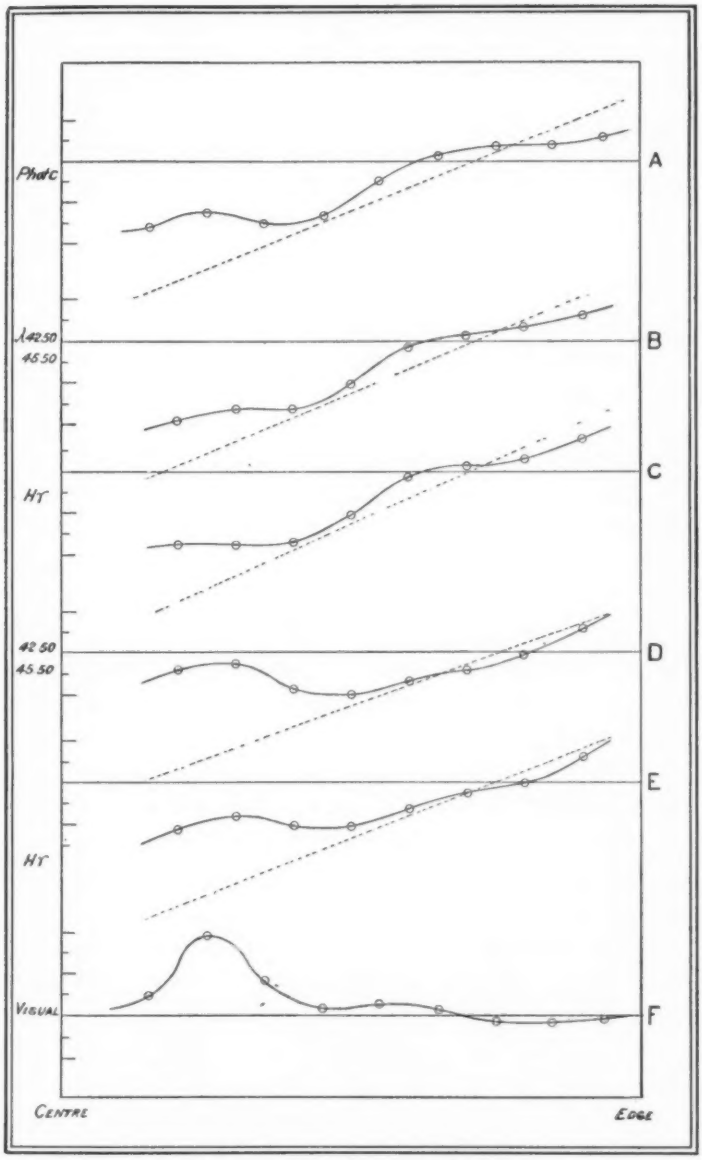


FIG. 3.—Zonal Differences of Focus

cally in curve *F* of Fig. 3. An examination of this curve shows that no point or focus is at a greater distance than 0.2 mm from the position

of mean focus, shown by the horizontal line, except a small region near the center of the objective, which has a longer focus. The effect of this region on the performance of the objective must, however, be exceedingly small, owing to its small area, less than one-tenth of the objective, and to the weak convergency of the pencils proceeding from it. In fact if Hartmann's criterion T[1] as to the quality of an objective be computed from the above mean values, it is found to be 0.141. According to this classification an objective is moderately ("mässig") good when T is greater than 1.5, good when T is between 0.5 and 1.5, and exceedingly ("hervorragend") good when T is less than 0.5. In the ideal, absolutely zoneless objective T is 0.

Evidently the objective when used visually is of the very first quality, and the aberrations appear only when it is used in conjunction with an auxiliary corrector for spectrographic work. Whether the aberrations there present are due to the correcting-lens, or to the objective when used in the photographic part of the spectrum, remains to be determined. For this purpose a further application of Hartmann's method was necessary to find the color-curves of the objective alone, and of the system of objective and correcting-lens for a number of zones. It was hoped that such observations would throw light on the cause of the aberrations and suggest a possible remedy. They would also serve as a check upon the zone-plate determinations, as, in this case, no spectral dispersion of the pencils could affect the accuracy of setting. To find such color-curves, the pencils of light coming from a zone plate fall on the spectroscope slit, and the distance between the resulting spectra taken with the slit within and beyond the focus gives a measure, calculated in the same way as before, of the focal position of any desired wave-length for any particular zone.

It was decided to determine the color-curves of eight zones of 38, 57, 76, 95, 114, 133, 152, 171 mm radius; and, to prevent the spectra from merging into one another, two zone plates were required, one (B), Fig. 2, of the four zones of 57, 95, 133, and 171 mm radius, and the other (C), Fig. 2, of the remaining four. The central openings were each 20 mm square, and the outer 20 by 25 mm. The zone plates were so placed on the objective that the row of openings was parallel to an hour circle, and the spectroscope was turned in

[1] *Zeitschrift fur Instrumentenkunde*, **24**, 46, 1904.

position angle until the slit was parallel to the openings, in order that irregularities in driving would not widen the spectra. To diminish the exposures as much as possible, bright stars, *Vega* and *Sirius*, were used and the slit was widely opened, as no inaccuracy would be thereby introduced in the distance between the spectra. The exposures were made on a night when the temperature was nearly stationary, and were arranged in the following order:

Plate 1;	Zone Plate	(*B*)	Fig. 2;	slit about	50	mm	within	the focus
2;		(*C*)	"	"	50	"	"	"	"
3;		(*C*)	"	"	40	"	beyond	"	"
4;		(*B*)	"	"	40	"	"	"	"

This procedure was followed to avoid as far as possible any relative displacement of the focal determinations of the two sets, due to slight changes of temperature of the objective. That no measurable displacement has occurred is shown by the continuity of the zonal curves of Fig. 3 drawn from the combination of the two separate determinations, and by their agreement with those made by the regular zone-plate method.

Each of these plates contains eight spectra side by side, one from each light pencil transmitted by the zone plate, and the position of the focus for each zone and for any desired wave-length in the range on the plate can be determined in exactly the same way as before. The hydrogen lines, in the first type stars used, serve as datum marks for the identification of wave-lengths, and measurements were made at eleven positions between λ 3970 and λ 5030. The corresponding focal points, as calculated from these measurements, are given in Table III for eight zones of the objective alone, and in Table IV for the same eight zones of the objective with correcting-lens, the latter being about 40 mm nearer the focus than its computed position.

The reason for using the correcting-lens below its computed position at once appears on inspection of Fig. 4, which represents, in their correct relative positions, the color-curves of a median zone of 108 mm radius, determined in exactly the same way as above. Curve *A* (Fig. 4) is the color-curve of the visual objective between the limits λ 6250 and λ 3970, which shows that the minimum focus is at about λ 5600, exactly in its computed position. Curve *B* is the color-curve of the system of objective and correcting-lens between λ 6250 and

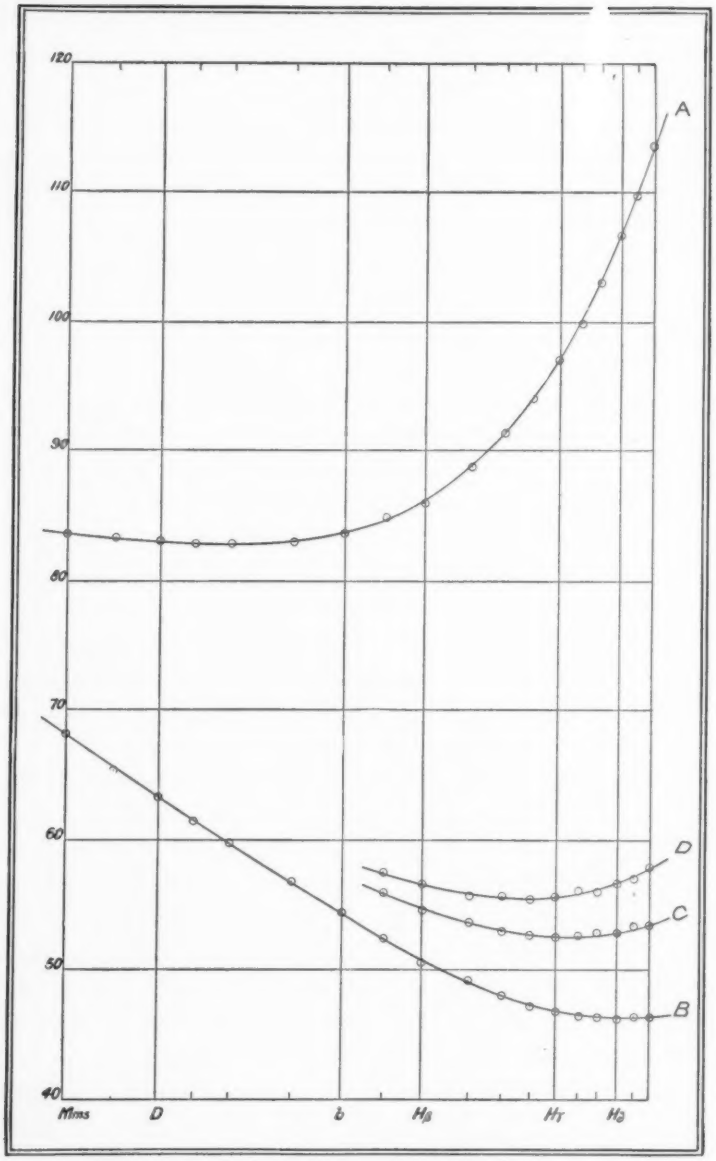


FIG. 4.—Color-Curves for a Median Zone

λ 3970, which shows that the minimum focus is at about $H\delta$, instead of $H\gamma$, its computed position. When the correcting-lens is moved

TABLE III

COLOR-CURVES OF OBJECTIVE ALONE

Radius of Zone	Wave-Lengths										
	5030	*Hβ* 4861	4680	4550	4440	*Hγ* 4340	4250	4175	*Hδ* 4102	4035	*Hε* 3970
38	85.57	86.87	89.64	92.02	94.28	96.30	99.78	102.48	105.82	109.59	110.96
57	85.30	86.30	88.95	92.00	94.28	96.60	100.25	102.74	105.95	108.75	111.61
76	83.84	85.78	88.76	91.09	93.67	96.39	99.50	102.34	105.31	108.69	112.31
95	84.67	85.42	88.41	90.82	93.56	96.34	99.37	102.61	105.68	109.11	112.12
114	84.38	85.78	88.68	91.16	93.87	96.77	99.58	103.06	106.19	109.63	112.65
133	84.71	85.93	88.68	91.08	93.91	97.16	100.21	103.16	106.72	110.11	113.08
152	85.06	86.29	89.18	91.49	94.41	97.42	100.53	103.71	106.79	110.10	113.38
171	85.41	86.87	89.65	92.03	95.02	98.04	101.29	104.62	107.81	111.10	114.53

TABLE IV

COLOR-CURVES OF OBJECTIVE AND CORRECTING-LENS

Radius of Zone	Wave-Lengths										
	5030	*Hβ* 4861	4680	4550	4440	*Hγ* 4340	4250	4175	*Hδ* 4102	4035	*Hε* 3970
38	55.12	54.75	53.11	51.18	50.65	50.92	50.92	51.17	51.36	51.68	51.91
57	53.38	53.89	52.55	51.98	51.24	51.04	50.90	50.91	50.95	51.30	51.82
76	54.51	53.67	52.54	51.60	51.19	51.14	51.16	51.11	51.20	51.46	51.26
95	55.57	54.37	53.16	52.46	51.95	51.70	51.60	51.74	51.96	52.30	52.66
114	55.45	54.82	53.62	53.12	52.79	52.59	52.65	52.79	53.03	53.24	53.31
133	55.94	55.10	53.88	53.33	53.06	52.89	52.93	53.05	53.31	53.60	53.73
152	55.84	55.13	54.05	53.54	53.26	53.07	53.25	53.38	53.49	53.62	53.64
171	56.05	55.39	54.38	53.90	53.60	53.53	53.56	53.97	54.15	54.27	54.34

down, away from the objective, some 40 mm we get curve *C*, and at 70 mm, curve *D*. In curve *C* the minimum focus is nearly at *Hγ*, and in *D* at λ 4460. Evidently the lowering of the correcting-lens some 40 mm effects considerable improvement in the color-correction without, as the earlier experiments showed, appreciably enlarging the image, and the lens has been used in this position almost from the first.

Although all the data in regard to the complete color-curves are given in Tables III and IV, still the actual curves drawn from these figures show all the conditions at a glance, and are hence worth giving. To prevent too great a confusion of lines, the curves for four zones only (zone plate (*B*), Fig. 1), of 57, 95, 133, 171 mm radius, are shown here in Fig. 5, the upper curves being of objective

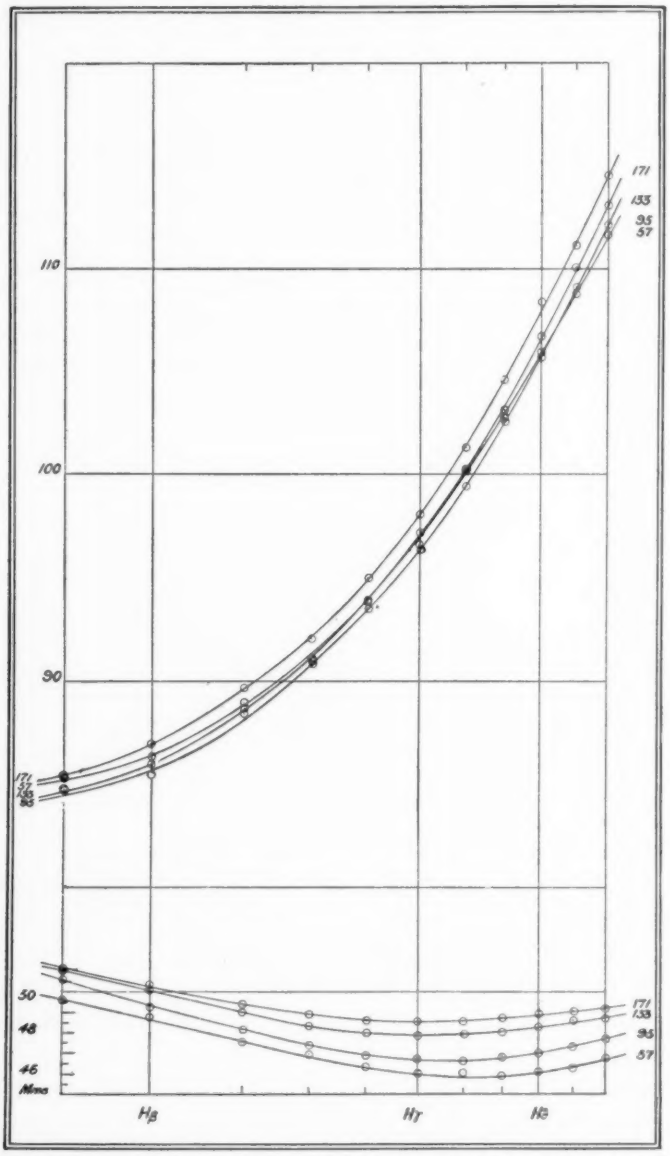


FIG. 5.—Color-Curves of Four Zones of Objective and of Objective with Corrector

alone, the lower of objective and corrector. These curves show at a glance that, in the photographic part of the spectrum, the focus for

the edge of the objective is longer than the focus for the center, that it has negative spherical aberration. This chromatic difference of spherical aberration is inherent in two-part objectives of the ordinary glasses, and the only remedy is to compensate for it by introducing the correct amount of positive aberration by the correcting-lens. However, the lower curves show that, instead of compensating for this chromatic difference, the correcting-lens has, on the contrary, increased it somewhat, and the focus for marginal rays is upward of 2 mm longer than the focus for central rays. This agrees almost exactly with the previous determination of the zonal foci of objective and corrector, and is good evidence of the substantial accuracy of the determinations. Before leaving these curves it may be pointed out that the crossing of the curve from the 57 mm zone over the others in passing from short to long waves is due to the longer focus of the central zones in the visual part and is further evidence in favor of the accuracy of the determinations.

To obtain a still more striking comparison of the cause and magnitude of the aberrations present in the system, the color-curves can be presented in another form, that of zonal foci curves like *A* and *F*, Fig. 3, previously determined. We have the color-curves, or the positions of focus, of the whole photographic region for eight zones of the objective in Tables III and IV, and these can be readily plotted in the same way and on the same scale as *A* and *F*, Fig. 3. If such curves were plotted for every wave-length in these tables, they would show a striking agreement in form, but I have satisfied myself with representing the positions of the focus of eight zones for $H\gamma$, the wave-length for which the system was computed, and for the mean of λ 4250, 4340, 4440, and 4550, the range of spectrum used here in velocity determinations. *E*, Fig. 3, is the curve for $H\gamma$ of the objective alone; *C* is the curve for $H\gamma$ of objective and corrector. *D* is the curve for λ 4250 to λ 4550 of the objective alone; *B* is the curve for λ 4250 to λ 4550 of the objective and corrector.

A comparison of curves *D* and *E* with *F* shows in a striking manner the chromatic differences of spherical aberration in the objective when used with photographic light. If we leave out of account or allow for the deviations in the central zones, we see that the focus of the outer is about 1.8 mm longer than the focus for the central

zones, a figure that agrees almost exactly with the computed difference as furnished me by Professor Hastings. A comparison of curves *A*, *B*, and *C* with *D* and *E* shows that this difference, instead of being removed or diminished by the introduction of the correcting-lens, has on the contrary been increased by about 0.6 mm, so that the difference in focus between outer and central zones is now about 2.5 mm, which, as before stated, will give a confusion disk nearly 2″ in diameter. I wish to point out, before leaving these curves, how the form of the curve is maintained throughout from *F* up to *A* except that the axis of the curve is inclined downward by the chromatic differences in the photographic region, and further tilted by the introduction of the correcting-lens. To show this I have dotted in approximate positions of such axes in the curves *E* to *A* to correspond with the horizontal axis in *F*. It will be noticed that the irregularities in the visual curve are continued throughout, but in an intensified form, as is to be expected when it is considered that the objective was computed and figured for visual work, and its use in the photographic region with an auxiliary corrector was only a secondary consideration.

I see no reason to doubt, however, if sufficient positive aberration were left in the correcting-lens to compensate for the negative aberration introduced by the chromatic differences, that the performance of the system could be much improved, although it is not likely, from the magnifying of the unavoidable zonal aberrations, that it would equal its visual quality. If the curve *A*, Fig. 3, representing the present condition of the system, could be tilted through the angle between the horizontal and dotted lines, by such a change in the correcting-lens, the resulting confusion disk would certainly have a diameter less than half its present magnitude, while the percentage of the incident star light transmitted by the slit would be considerably increased, probably doubled, with a proportionate diminution of the required exposure times for stellar spectra.

Such an improvement would be well worth considerable effort, and I have been in communication with the Brashear Company and with Professor Hastings to that end. With their well-known willingness, I may even say anxiety, to produce the highest quality of optical work and to make any improvements that may be suggested

to them, the Brashear Company are undertaking to make a new correcting-lens to computations by Professor Hastings, to whom I I am very much indebted for criticisms and suggestions on the present paper. I may say that Professor Hastings finds a very marked agreement between his computed data of the objective, color-curves, and chromatic differences, and my observations. He explains the failure of the correcting-lens to compensate for the chromatic differences of focus, which it was computed to do, by the fact that this lens has to correct the errors of an objective of nearly fifty times the area, that the small departures of the wave-surfaces from a true sphere have grown enormously when these surfaces have contracted to one-fiftieth their original area, and that a very perfect correction by spherical surfaces can hardly be hoped for. He thinks, however, that considerable improvement can be effected, and I have no doubt myself that he and the Brashear Company can do much better than he says when they have quantitative values of the existing aberrations.

The reason for publishing this paper in its present incomplete form, before the new correcting-lens is ready, is to bring before stellar spectroscopists the important matter of the size and character of the star image given by their telescopes. I have gone fully into the details of the investigation and explained the difficulties that arose with the means of overcoming them, in order to smooth the way for similar investigations into the character of the star image given by other systems of objective and correcting-lens. It seems to me extremely probable that, in the major part if not all of the telescopes employed in spectrographic work, aberrations of the same or a similar nature are present. If a correcting-lens computed to compensate for the chromatic difference fails in one case, it is possible, even probable, that it may fail in others. Another basis for this belief is a comparison of the relative exposure times required for different installations taking into account size of object-glass, slit-width, and dispersion of the spectrograph. I am well aware that such a comparison must necessarily be incomplete, and the results reached subject to an uncertainty, say, of 25 per cent., owing to the difficulty of comparing different installations under different conditions of seeing, etc. We have already seen how important a part is played by atmospheric disturbances in enlarging the star image so that the linear

diameter of the image increases nearly in proportion with the focal length, and therefore approximately, as the ratio of aperture to focal length does not vary much in large instruments, with the diameter of the object-glass. Consequently, the effective value of increase of aperture is not proportional to the increase of area, but more nearly to the increase of diameter, which was accordingly used in the comparison. So far as regards the relative dispersion of different instruments, the exposure time was taken as directly proportional to the linear dispersion, presuming the same height of spectrum in each case. No account was taken of the difference in the loss due to absorption and reflection in the prism-train, although this may be quite important in some cases. The exposure time required was taken as inversely proportional to the slit-width, and this, as one of the experiments detailed above shows, is probably nearly in accordance with the facts. In the following Table V, data of the various equipments which are and have been used in radial velocity work, so far as they were available to the writer, appear, but these data are incomplete and may in some cases be in error, although probably not to a marked degree.

TABLE V

COMPARISON OF EFFICIENCIES OF INSTALLATIONS

Equipment	Diameter of Objective, inches	Ratio of Diameters	Ratio of Areas	Linear Dispersion, mm per Tenth Meter	Slit-Width, mm.	Theoretical Exposure	Actual Exposure Required		
							β Ophiuchi	*γ Aquilae*	*α Boötis*
Ottawa	15	1	1	18.6	0.025	1	50m	60m	6m
Yerkes	40	2.67	7.1	10.8	.038	0.42	75	115	15
Lick	36	2.4	5.76	12.5	.025	0.62	25?	25?	4?
Lowell	24	1.6	2.56	11.4	.025	1.02	120	120	20?
Newall	25	1.67	2.78	14.6	.025	0.76	70	75	15
Bonn	12	0.8	0.64	15.2	.020	1.91	75	75	15
Pulkowa	30	2.0	4.0	13.0	.020	0.89	65?	65	15
Lord	12½	0.83	0.69	18.6	.025	1.20	60?	60?	4

The above comparison shows that the Lick, Bonn, and Lord equipments *in practice* approach more nearly the theoretical efficiency than the Ottawa, but the Yerkes, Lowell, Newall, and Pulkowa depart farther from it.

There seems therefore reasonable ground for believing that considerable improvement in the efficiency, and considerable increase in the range of the majority of spectrographic equipments can be attained by looking into the character of the star image given by the condensing system. Although the exact effect of atmospheric disturbances on the effective diameter of the star image is difficult of determination, I feel satisfied, if I can obtain a correcting-lens that will give a star image reasonably free from aberration, that the exposure times required here can be very materially reduced, I hope by 50 per cent., and I see no reason why a similar or even greater improvement could not be effected in some of the other equipments.

I acknowledge with pleasure my indebtedness to Dr. W. F. King, the Director of the Observatory, for help and encouragement in the prosecution of the work, and to Mr. W. E. Harper for making duplicate measures for comparison purposes on some of the test plates.

DOMINION OBSERVATORY, OTTAWA
January, 1907

ON A NEBULOUS GROUNDWORK IN THE CONSTELLATION *TAURUS*

By E. E. BARNARD

I have elsewhere at various times called attention to the connection of nebulosities with some of the vacant regions of the sky. The finest example of this remarkable and suggestive peculiarity is shown in the great nebula of ρ *Ophiuchi*. In connection with some of these vacant regions I have remarked on the singular fact that in some cases—especially in the regions of θ and ρ *Ophiuchi*—these vacancies are vacancies only in the apparent absence of stars, for they are really often filled with a luminous veiling in which darker perforations occur.

The extraordinary vacant lanes among the Milky Way stars, in *Ophiuchus* and elsewhere, have often suggested that they are not only devoid of stars, but that they are darker than the immediate sky. In some cases there has been a suspicion that this was a matter of contrast, and that, if the remaining stars were removed, the lanes would also disappear. While this might be true in some cases, there are others where the appearance is strictly conclusive that the vacancies are not only due to the absence of stars, but that the channels are in a bed-work or nebulous substratum, and that, if the stars were removed, the lanes would still exist.

It will be seen that much importance depends upon whether these lanes are subjective—due to the scarcity of stars alone—or whether they reveal to us a nebulous substratum in certain parts of the sky,

In some of my early photographs north and east of the *Pleiades* the plates showed the existence of peculiar lanes far to the east of the cluster. Opportunity did not offer itself until the past winter to investigate their peculiarities by photography.

In the first part of January of this year I made several long exposures which covered the region in question. The result is very striking, and I believe of great importance; for the plates show that these lanes are undoubtedly in a substratum of some kind, as well as among the stars themselves.

The dying-out of nebulae—since it does not seem any longer necessary to use these vast bodies of gaseous matter for the making of suns—is a probability fully as warranted as the belief and certainty that the stars must die out. What would be the condition of a nebula that no longer emitted light, is a question; but as this light in all probability is not the product of heat or combustion in the ordinary sense, it is likely that we should simply have a dark nebula which would not be visible in the blackness of space unless its presence were made known by its absorption of the light of the stars beyond it—if this absorption were sufficient to be effective.

We have rather looked upon the nebulae as transparent bodies, like the comets; but there are no observations to warrant this idea, since in no case do we know that a nebula is on this side of the stars or beyond. True, there are cases where a star is palpably involved and seen through at least a portion of the nebula. There is nothing, however, to show whether the light of such a star has not been very greatly reduced by the interposition of the nebulous matter, and whether a much smaller star would not have been entirely invisible through the veiling of nebulosity.

This idea of the absorption of the light of the stars by a dead nebula or other absorbing matter has been used by some astronomers as an explanation of the dark or starless regions of the sky. Though this has not in general appealed to me as the true explanation—an apparently simpler one being that there are perhaps no stars at these places—there is yet considerable to commend it in some of the photographs.

The immediate neighborhood of the great nebula of *ρ Ophiuchi*—as if the outer boundaries of it were devoid of light—is a good example of an apparently absorbing medium by the dying-out of the outer portions of the nebula.

From their appearance in the sky, I believe the nebulae in general are transparent, yet there are some cases, especially among the planetary nebulae, where the appearance is quite otherwise.

The beautiful veil of nebulosity extending from the star *ν Scorpii* strongly gives the impression of a dulling of the light of the stars in that direction. To all appearances fewer stars seem to be within the boundaries of this nebula, as if the fainter stars were

blotted out and the brighter ones diminished in luster. If this is not a delusion of some kind, it would appear that this nebula is between us and the groundwork of small stars here.

The connection of nebulosities with vacancies, and the apparent mingling of the outer portion of the nebula with the darkness of the sky, as if that darkness were something really tangible, as suggested in the case of the nebula of *ρ Ophiuchi*, is an extremely important feature, from which I believe there will some day develop facts of the greatest importance in explaining the real structure of the heavens. It would therefore be a very valuable work to locate all these regions and to secure the best long-exposure photographs of them. In this way a consistent study of their peculiarities may be made by those interested in their nature. Of late years I have endeavored to find as many of these places as possible. This has resulted in the development of the extraordinary regions of *Ophiuchus* and *Scorpio*, where these singular features are perhaps best shown.

It was in the order of this investigation that I made the photographs given in the present reproductions.

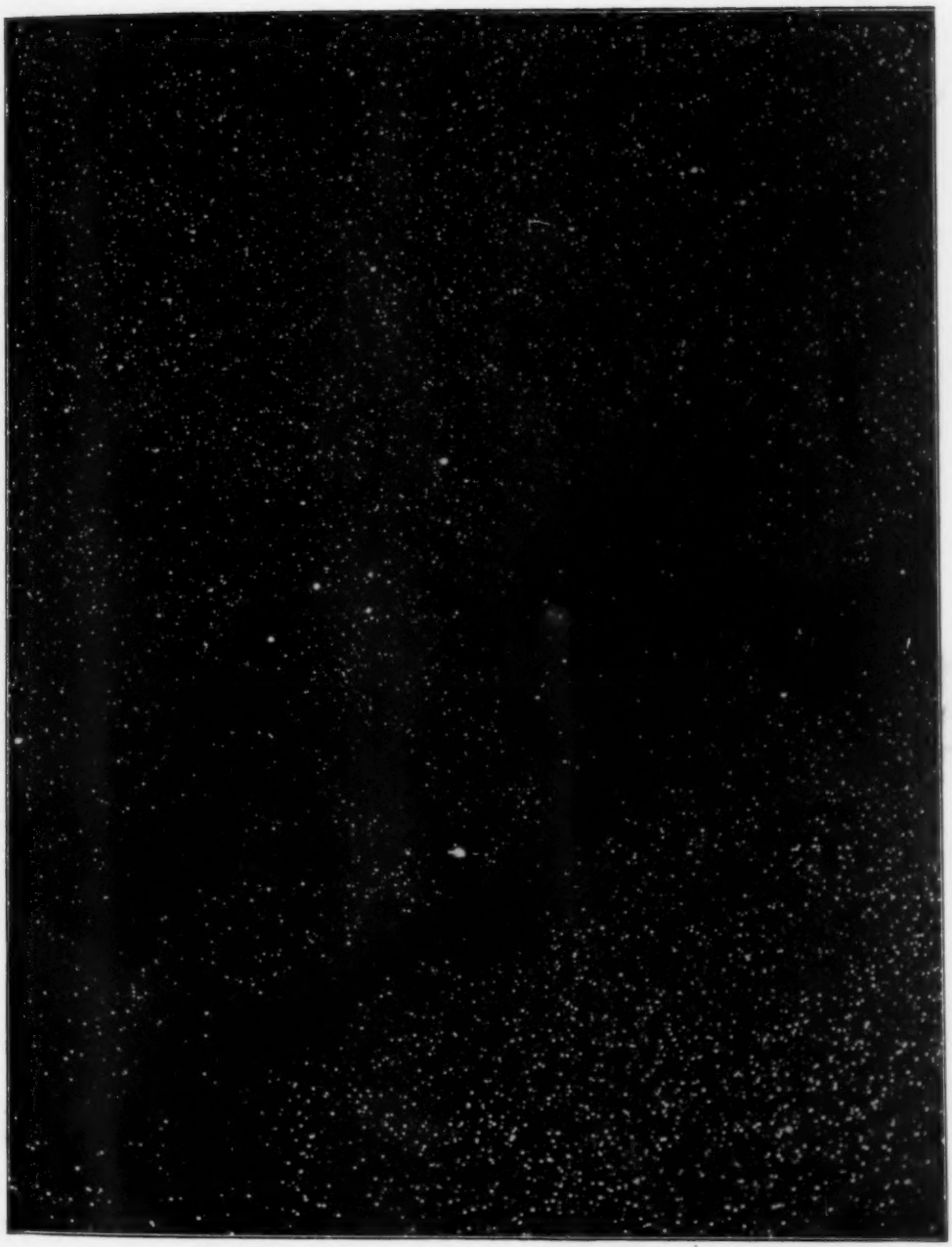
The region here shown is extraordinary. The narrow vacant lanes are as singular examples of the peculiarities I have mentioned as any that I know of, and they show perhaps even better the fact that the lanes actually exist in the sky independent of the stars. Besides the lanes referred to, the photographs show a large nebula apparently in a hole almost devoid of stars, from which one of the lanes runs away to the southeast for several degrees.

The pictures seem to show that the brighter part of this nebula is only a small portion of it, and that the nebula is feebly luminous over most of the vacancy; a longer exposure will perhaps prove this to be true. The feebler portions of the nebula would almost suggest the idea that a large nebula exists here, but that the major portion of it is dead or non-luminous, and that it actually causes the apparent vacancy by cutting out the light from the stars, while the few stars visible are perhaps on this side of the nebula. I give this simply as what the picture would suggest to one, and not as what may really be the truth.

On the original negative with the 10-inch lens, in the brightest part of the nebula there is a perfectly circular disk slightly brighter

PLATE XI

N



E W

VACANCY AND NEBULA IN *TAURUS*

10-inch Lens. 1907, January 9, $12^h\ 27^m$ to $17^h\ 55^m$ G. M. T. Enlarged 1.6 times. Scale: 1° = 35 mm.

than the rest, as if a large planetary nebula were involved. This is so sharply defined, however, that I doubt its reality. For verificaton it must wait until the end of the year when more photographs can be secured. The scale of the 6-inch plate is too small to aid in the verification.

I have been slow in accepting the idea of an obscuring body to account for these vacancies; yet this particular case almost forces the idea upon one as a fact. There are portions of this apparent vacancy that are certainly darker than the adjacent sky. There is no question that this is real, and not a subjective effect, because, as will be seen later, the dark lane running from it shows similar markings, which are certainly darker than the sky, and this is the case with the lane itself. If we examine this lane, we shall find that it comes to an abrupt stop at a point in

$$\alpha = 4^h\ 16^m, \quad \delta = +26°0.$$

But there is no change in the sky here; it is uniform with the rest of the sky among the stars, and is decidedly brighter than the lane. A half degree farther on and the lane reappears in a broken and straggling manner.

These lanes are best shown in the small picture (Plate XII) taken with the 6¼-inch lens. This plate is simply to show the extent and general appearance of this remarkable system of lanes. Other photographs which I have made, especially those on February 7, 1907, show that this plate includes the full extent of these vacancies, the rest of the sky nearby being free from them. The region is comprised between the limits

$$\alpha = 4^h\ 0^m \text{ to } 4^h\ 54^m \text{ and } \delta = +24° \text{ to } +28\tfrac{1}{2}°.$$

There is a larger vacancy, similar to the one in which the large nebula occurs, in about the position

$$\alpha = 4^h\ 31^m, \delta = +25°7.$$

It shows considerable dark detail. In it is a small nebula which looks as if it might be only the brighter portion of a larger nebula filling or partly filling the vacancy. The position of this nebula is:

$$\alpha = 4^h\ 31^m, \quad \delta = +25°\ 25'.$$

Perhaps the most singular of these lanes is the one that straggles along almost east and west

from $\alpha = 4^h\ 0^m$, $\delta = +24\frac{1}{2}°$ to $\alpha = 4^h\ 26^m$, $\delta = +24°$

near the lower part of Plate XII. It is quite definite. A long strip of it, from $4^h\ 8^m$, $+25°$, to $4^h\ 16^m$, $+24\frac{1}{2}°$, is singularly well defined, especially at the east end, where it abruptly stops and disappears for a space of nearly a half-degree, after which it reappears in a very broken manner farther on, until it enters a considerable region almost devoid of stars, where it appears as a series of irregular black spots. Where this lane is interrupted it shows still more clearly that the lane itself is darker than the sky. These lanes and holes, therefore, would still be seen if the stars were all removed. This of course implies that a substratum of some kind exists all over this part of the sky, and that these are lanes and holes or rifts in it. A very singular feature in this connection is that the stars also are absent in general from these lanes.

Now, the question is: Does this substratum consist of nebulosity, which would be the natural conclusion, or is it something else, as to the nature of which we do not yet know anything?

It almost seems to me that we are here brought face to face with a phenomenon that may not be explained with our present ideas of the general make-up of the heavens. The conditions exemplified here also exist in the region of the dark holes and lanes near θ and ρ *Ophiuchi*, but they perhaps do not so clearly show the presence of a groundwork other than that due to stars, as the present case does, although the phenomena there are more remarkable, or rather they are more spectacular.

Among the most surprising things in connection with these nebula-filled holes are the vacant lanes that so frequently run from them for great distances. These lanes undoubtedly have had something to do with the formation of the holes and with the nebulae in them. The idea of the dying-out of a nebula, previously mentioned as a possible explanation of the vacancy, is not strengthened by the presence of the lanes, for we do not find in general any great streams of nebulosity extending away from the nebulae. A possible exception is the case of the great curved stream of nebulosity which seems to

PLATE XII

N

E W

REGION OF VACANCIES IN *TAURUS*

6-inch Lens. 1907, January 9, $12^h\ 27^m$ to $17^h\ 55^m$ G. M. T. Not enlarged. Scale: $1° = 13$ mm.

emanate from the great nebula of *Orion*, and which stretches away for many degrees northward over a large part of the constellation.

The position of the center of the large plate (Plate XI) is

$$\alpha = 4^h\ 11^m.5, \quad \delta = +27°.9;$$

that of the small plate (Plate XII) is

$$\alpha = 4^h\ 15^m, \quad \delta = +27°.6.$$

The brightest portion of the large nebula is at

$$\alpha = 4^h\ 10^m, \quad \delta = +27°\ 55'.$$

As a ready means of identification, the following refer to the small plate.

The two stars near the south edge are

B. D. +22°.696,	$4^m.5$,	$\alpha = 4^h\ 17^m\ 38^s.6$,	$\delta = +22°\ 28'.3$
+22.699,	6.2,	$\alpha = 4\ 18\ 37.5$,	$\delta = +22\ 39.3$.

The star at the southeast corner of the plate is

B. D. +22°.712, $7^m.4$, $\alpha = 4^h\ 26^m\ 5^s.3$, $\delta = +22°\ 22'.5$.

The two conspicuous stars near the right-hand edge are

B. D. +27°.633,	$5^m.1$,	$\alpha = 3^h\ 57^m\ 43^s.7$,	$\delta = +27°\ 13'.6$;
+28.619,	5.4,	$\alpha = 3\ 58\ 3.9$,	$\delta = +28\ 36.8$.

The two close to the upper edge are:

B. D. +32°.805,	$7^m.3$,	$\alpha = 4^h\ 20^m\ 46^s.3$,	$\delta = +32°\ 11'.8$;
+32.806,	6.5,	$\alpha = 4\ 21\ 20.3$,	$\delta = +32\ 8.0$.

In the large plate, the conspicuous star below the middle is

B. D. +27°.655, $\alpha = 4^h\ 11^m\ 27^s.0$, $\delta = +27°\ 0'.1$.

The less conspicuous star above the middle is

B. D. +28°.642, $\alpha = 4^h\ 11^m\ 37^s.9$, $\delta = +28°\ 32'.9$.

These plates contain the trail of an asteroid, which also shows on the plates of January 5.

Following are the approximate positions of this object, obtained from the *B.D.* charts. They, like all the positions in this paper, refer to the epoch 1855.0.

1907, January 5, $14^h\ 23^m$ G. M. T.	$\alpha = 4^h\ 13^m.5$,	$\delta = +28°\ 35'$;
9, 15 11 G. M. T.	$\alpha = 4\ 12.5$,	$\delta = +28\ 24$.

The trails are very strong, showing the asteroid to be a bright one. The trail will be found on the plate made with the 10-inch (Plate XI) at a distance from top, 66 mm (2.6 inches), from the left, 56 mm (2.2 inches)

A much brighter asteroid is shown on the plate of this region on

1907, February 7, $14^h\ 40^m$ G. M. T., $\alpha = 4^h\ 17^m$, $\delta = +22°\ 55'$.

Should it be desired, more accurate places can be obtained by measuring the plates.

On the photographs of February 7 the sixth-magnitude star *B.D.* $+22°699$ has a thin nebulous wisp running from it to the northeast some 6′ or 8′.

The position of this star from the *B. D.* is

$$6^m.2, \quad \alpha = 4^h\ 18^m\ 37^s.5, \quad \delta = +22°\ 39'.3.$$

The star *B. D.* $+28°645$, $9^m.1$, $\alpha = 4^h\ 12^m\ 55^s.8$, $\delta = +28°\ 6'.1$, has two nebulous tails. The brightest of these is in the direction of position angle 330°. The other one is at right angles to this, in position angle 60°. These comet-like tails are about 6′ or 7′ long. They are shown on the larger reproduction, where the star will be found 76 mm (3.0 inches) from the top of plate and 51 mm (2.0 inches) from the left-hand side.

The large scale photograph (Plate XI) was made with the 10-inch Brashear lens of the Bruce telescope, and the smaller one (Plate XII) was made with the 6¼-inch Voigtländer of the same instrument. The exposures were from $6^h\ 27^m$ to $11^h\ 55^m$, Central Standard Time, 1907, January 9, the duration of exposure being $5^h\ 28^m$.

The defect at the left-hand side of the bright star *B. D.* $+27°655$ on the large plate was due to trouble with the driving-clock, caused by the cold.

In the smaller scale picture there are certain inequalities of illumination due to the reproduction, which will deceive no one.

NOTE ADDED TO PROOFSHEETS

In observing Swift's periodic comet on 1892 January 18 with the 12-inch refractor of the Lick Observatory, I found a *very, very* faint nebula in the position

$$1855.0, \quad \alpha = 4^h\ 31^m\ 9^s \pm, \quad \delta = +25°\ 26'.3.$$

I have a note which says:

"Both the nebula and the comet are seen on a nebulous background—a vast nebula. The position [of the small nebula] cannot be far from the brightest portion of this great nebula. The small nebula is most excessively difficult."

This description agrees with the small nebula described previously in the position $\alpha = 4^{h}\ 31^{m}$, $\delta = +25^{\circ}\ 25'$. It also shows that the great nebulosity is easily visible in a 12-inch telescope.

YERKES OBSERVATORY
March 9, 1907

Minor Contributions and Notes

AGNES MARY CLERKE

Agnes Mary Clerke was born on February 10, 1842, at Skibbereen, a small country town in a remote part of the County Cork. Her father was John William Clerke, and her mother was a sister of the late Lord Justice Deasy.

Constitutionally delicate, Agnes Clerke from her earliest years, as so often is to be noticed in cases of frail health, found her chief delight in literary study and in music. From quiet talks often enjoyed with her in her later life it was clear that her thoughtfulness and her liking for probing difficult problems must have developed early.

In 1861 the Clerke family moved to Dublin, and in 1863 to Queenstown. The winters of 1867 and of 1868 were spent at Rome, that of 1871 at Naples, and the next five winters at Florence; the summers of 1874–76 being passed at the Bagni di Lucca. The sisters, Agnes and Ellen, both profited to the full from this sojourn in Italy, as their subsequent writings show; but Agnes at Florence worked specially hard, reading constantly in the public library there, and always, I believe, with one great object before her.

It is a question of much interest to examine into the early leanings and aspirations of those who distinguish themselves later, and Agnes Clerke early determined her life-work. Before leaving Skibbereen, at about the age of fifteen, she had clearly before her the intention of writing a history of astronomy, and it is thought had actually written a few chapters. Her first article in the *Edinburgh Review* is in harmony with the above facts.

Agnes Clerke's literary life may be said to have begun in 1877 with the acceptance of her article "Copernicus in Italy," by Henry Reeve, then editor of the *Edinburgh Review*, who recognized the value of his new contributor and kept her at work. The number of her contributions to the *Edinburgh* is fifty-five; and they are all of the highest order.

PLATE XIII

AGNES MARY CLERKE

Agnes Clerke, with her family, returned to England in 1877, and settled in London. With the publication of the *History of Astronomy* in 1885 may be said to have begun her astronomical life. She read systematically, and cultivated personal relations with a wide circle of astronomical workers, in person or by correspondence. I consider that these relations had much to do with the success of her work. Her sympathies were so keen, her interest so warm, her longing for further truth so intense, that everyone liked to offer her all he could.

In 1890 appeared her second book, *The System of the Stars*. The progress of science and the growth of its literature during the last quarter of a century have been so enormous that a new order of worker is imperatively called for; and Agnes Clerke was an admirable example of such a worker, devoting herself to astronomy, which is at once the oldest and, in its new developments, the youngest of the sciences—the science which Poincaré has lately so eloquently declared to have given the conception of *law* to all the others. The mission of these special workers is to collect, collate, correlate, and digest the mass of observations and papers; to chronicle, in short, on one hand, and, on the other, to discuss and suggest, and to expound; that is, to prepare material for experts, to inform and interest the general public. There is urgent need of a better-educated public opinion in this country. That such a mission may be a splendid and fruitful one has been shown by Agnes Clerke; what careful preparation it requires, and how much it demands of those who would enter upon it, her career also shows.

The immense increase in astronomical literature is hardly realized except by those engaged in dealing with it. To give but one instance, *The Annual Index of Astronomical Literature* for 1905, published under the auspices of the *Astronomische Gesellschaft*, contains over two thousand references collated from three hundred separate publications.

The strain of such work as I am indicating is great indeed, involving as it should the power of holding loose in the mind, so to speak, an immense mass of facts, and also a power of rapidly associating or dissociating them as work and discovery may suggest. In one of her latest works, *Modern Cosmogonies*, Agnes Clerke herself dwelt upon this strain. "Year by year," she says (p. 160), "details accumulate,

and the strain of keeping them under mental command becomes heavier." Pathetic words, written almost in blood! For, not long before had been published her last large work, *Problems in Astrophysics*, a work she feared she could not live to complete; a work which she was able to toil at for only half an hour at a time.

All through her life Agnes Clerke was a student. Lectures and Friday evening dicourses at the Royal Institution, which bore upon her work, she was careful to attend. A three-months' visit to Sir David and Lady Gill at the Cape in 1888 gave her some observatory opportunities which increased her power of clearly realizing the records of observatory and laboratory work.

She was awarded by the Royal Institution, in 1892, the Actonian Prize of 100 guineas for her works on astronomy; and in 1903, she received the distinction of being elected an honorary member of the Royal Astronomical Society—an honor and title held previously only by Mrs. Somerville, Caroline Herschel, and Ann Sheepshanks. A frequent attendant at the meetings of both the Royal Astronomical Society and the British Astronomical Association, she was always an interested one. Occasionally she spoke; but she had no liking for speaking in public nor indeed was she well suited for it.

A complete list of Agnes Clerke's papers it would be difficult to compile. They were in truth innumerable. Her articles on astronomers for the *Dictionary of National Biography*, articles for the *Encyclopaedia Britannica* and for other encyclopaedias, were many, and all of them were models of painstaking inquiry and of clear, concise statement. The more important of these are of lasting interest and value.

Her larger works are: *History of Astronomy in the Nineteenth Century* (four editions); *The System of the Stars* (two editions); *Familiar Studies in Homer; The Herschels and Modern Astronomy; Concise History of Astronomy; Modern Cosmogonies; Problems in Astrophysics.*

I venture to think that the *History of Astronomy in the Nineteenth Century* is the most important of her works. It is admirable in its completeness of references, its wide inclusiveness, and in its lucidity. It deserves to live, and it assuredly will live—the invaluable continuation of Grant's fine work. *The System of the Stars* and the *Problems*

in Astrophysics are works of a different order. Treasuries of knowledge and of suggestion they certainly are.

The *Homeric Studies*, except in one chapter, are not specially astronomical, but they are evidence of breadth of culture and of wide intellectual interest, and are full of delightful touches of wit and of humor.

It seems to me a mistake to regard Agnes Clerke's smaller works as of less importance than her larger ones. I have said that I consider the *History* her greatest work. But in some respects I venture to think that her greatest achievement is *Modern Cosmogonies*. I claim for this book that it is not only a history, but a work of philosophical thinking and of imaginative insight of a very high order. Its small size is an accident. It is a work essentially great. In these brilliant sketches Agnes Clerke's style is at its best. But the writing in *Modern Cosmogonies*, good as it is, is a small matter compared with the masterly grasp of, I may say, all things and of their interrelations which the work reveals. And where else is shown, in recent philosophical writing, such vision and faculty divine for seizing and pointing out the reasonable spiritual clues, set in what we call Nature—clues helping to sustainment of soul in the midst of the majestic mysteries surrounding us?

No sketch of Agnes Clerke would be complete without reference to her love of music. To her music was in the highest sense of the term a recreation. She turned to it for very life. Her piano-playing was truly musicianly, and her repertory was large. Perhaps her playing was at its best in rendering Chopin. As an accompanist she excelled. Her teachers were, in Dublin, Miss Flynn; in Florence, Buonamici.

Remarkable as were the intellectual powers of Agnes Clerke, her moral endowments were equally so. It was a question we frequently debated—the influence of character on work; and as I write the memory of certain talks is hauntingly present. As is the heart, is the work. The best work is and must be associated with lofty character. It was so with Agnes Clerke. No purer, loftier, and yet more sweetly unselfish and human soul has lived. She was so incapable of meanness that she even incurred danger as a historian in crediting too readily all workers with her own high ideals.

As a friend and companion she was faithful and true, and full of charm; and without her the world to those who had her friendship seems darkened and empty.

But her mission, I believe, had been fulfilled. For twenty years she had been to modern astronomy an admirable historian, and had kept before working astronomers clear charts, so to speak, of what was being done, and of what should and might be done. In so doing she rendered splendid service, and inaugurated a kind of work which must be more and more needed—a kind of work which not only advances astronomy, but promotes a universal brotherhood and co-operation, golden indeed.

Agnes Clerke's death comes as a shock to many. A cold—I fear not sufficiently nursed at first—led to pneumonia and complications, and, in spite of all that devoted love and skill could do, she passed gently to the next life, peaceful and fully conscious almost to the last, on the morning of January 20, 1907.

MARGARET LINDSAY HUGGINS

FEBRUARY, 1907

REMARKS ON HULL'S OBSERVATIONS OF THE DOPPLER EFFECT IN CANAL RAYS

Professor G. F. Hull recently published in this *Journal* an investigation of the influence of electrical fields upon spectral lines.[1] In his paper he also communicates his observations on the spectra of the canal rays, which led him in several points to negative results, where I had obtained positive results.

In the summer of 1906 I made a brief announcement that I had observed a slight polarization in the line-spectrum of rapid canal rays.[2] Mr. Hull does not find this polarization. I shall later report in an extensive paper as to the phenomenon which I announced.

I have already published *in extenso* my observations upon the Doppler effect on canal rays. Mr. Hull succeeded as I did in finding the Doppler effect in the case of hydrogen.[3] I further demonstrated

[1] *Astrophysical Journal*, **25**, 1, 1907.

[2] *Verhandlungen der deutschen physikalischen Gesellschaft*, **8**, 105, 1906.

[3] *Annalen der Physik*, **21**, 401, 1906; *Astrophysical Journal*, **25**, 23, 1907.

the presence of the Doppler effect for a number of mercury lines;[1] but Mr. Hull does not find the effect in the case of mercury or helium.

Regarding this difference it should be first remarked that the problem of demonstrating the Doppler effect in canal rays is rather electrical than spectroscopic. It is not necessary to employ a spectrograph of a large dispersion; it is sufficient, and indeed preferable, to use a grating or prismatic instrument of moderate dispersion and great light-power, since the Doppler effect, if it occurs at all, is always of considerable magnitude in the case of canal rays. But, on the other hand, it is necessary, to satisfy the condition that the cathode-drop producing the canal rays shall not be less than a certain limiting value.

When the line-spectrum of the canal rays has been photographed in the direction of translation, the experimenters have found, in all cases yet investigated,[2] an undisplaced ("stationary") line, and beside it a band of displaced ("movable") lines; while between the line at rest and the band of moving lines the density of the photographic plate shows with sufficient dispersion a minimum of intensity.

It is singular that Mr. Hull has overlooked, or at least not described in his paper, these two important things—the simultaneous appearance of stationary and movable intensity, and the appearance of the minimum of intensity. He does not seek in his spectrograms for the movable line beside the stationary line, which always appears with more or less intensity, but he compares the position of the maximum of intensity of the line on the photograph of the canal rays with the position of the maximum on the photograph of the positive column of an ordinary mercury tube or helium tube. Inasmuch as the stationary intensity is greater than the movable intensity, even for large velocities, certainly for mercury, and probably also for helium, it would appear that Mr. Hull had made his comparison between the stationary line in the spectrum of the canal rays, and the stationary

[1] J. Stark, W. Hermann und S. Kinoshita, *Annalen der Physik*, **21**, 462, 1906.

[2] Hydrogen: J. Stark, *loc. cit.;* B. Strasser and M. Wien, *Physikalische Zeitschrift*, **7**, 744, 1906; F. Paschen, *ibid.*, **7**, 924, 1906.
Mercury: Stark, Hermann, and Kinoshita, *loc. cit.*
Nitrogen: W. Hermann, *Physikalische Zeitschrift*, **7**, 567, 1906.
Hydrocarbon: S. Kinoshita, *ibid.*, **8**, 35, 1907.

lines of an ordinary Plücker tube, without noticing this fact. It can then be understood why he has not found the slightest displacement between the two stationary lines. He ought to re-examine his spectrograms of the canal rays and see if he cannot detect beside the stationary lines some very faint lines (diffuse bands), the movable lines, or the Doppler effect.

If he should thus find that there was certainly no Doppler effect in his canal rays in mecury vapor, then this genuine negative result can be explained, for he does not seem to have satisfied the following important condition for the appearance of the Doppler effect.

If, during the greater portion of the exposure time, the cathode-drop is smaller than that which communicates to the canal rays just the velocities which correspond in the Doppler effect to the width of the intensity-minimum, then the displaced intensity is too slight, and hence no Doppler effect will appear, only the stationary or undisplaced line being observed. In order, therefore, to obtain the Doppler effect at all, the cathode-drop should not be allowed to fall below a certain minimum value during any considerable part of the whole exposure time.

I have further shown that the ratio of the displaced to the stationary intensity increases with the velocity of the canal rays, or hence with the amount of the cathode-drop. For mercury lines this ratio is very small for small values of the cathode-drop, whence the stationary intensity is large in proportion to the displaced intensity. A moderately long exposure for a relatively small cathode-drop can therefore probably bring out the stationary line in considerable intensity on the photographic plate, while the movable line (Doppler effect) remains invisible. For two reasons, therefore, careful attention must be given that the cathode-drop does not fall below a certain value during the whole of the exposure. There is therefore no value in establishing that the potential (cathode-drop) had a very high value during the exposure, if at the same time a precaution was not taken that it did not during the exposure sink below a certain value for some time. After I had recognized the relation between the velocity of translation and the intensity of radiation, I and my collaborators (Messrs. Hermann, Kinoshita, and Siegl) have in all photographs of the Doppler effect (in *H*, *Hg*, *Na*, *Ka*, *N*, and *C*), in the full appreciа-

tion of its necessity, attended to the fulfilment of this condition with painstaking care. In our papers we have always stated that during our exposures the cathode-drop was not allowed to fall below a definite and quite high value; and I may here add the remark that for us the problem of the proof of the Doppler effect in a line-spectrum has reduced itself to the satisfaction of that electrical condition. The spectroscopic technique may be regarded as secondary to the satisfaction of this condition. Mr. Hull does not anywhere mention in his paper that during exposure he did not permit the cathode-drop to fall below a certain value for some time. He does say in several places that the tension in his experiments with the induction coil reached a high value, and he also estimates with the aid of a spark-gap the tension at the canal-ray tube. A spark-gap, however, gives only a maximum value of the tension, and does not control the fall below a definite minimum value. Nothing is said in Mr. Hull's paper as to whether he has done this; and if a revision of his spectrograms should again lead to actually negative results, it is to be assumed that he has not satisfied that condition. I myself have made no investigations on helium, but for mercury lines at λλ 4358, 4078, 4047, 3663, 3655, 3650, 3341, 3131, 3125, 3021, 2967, and 2536 the Doppler effect in the canal rays has been unquestionably demonstrated by myself and Messrs. Hermann and Kinoshita. We have three photographs taken with the concave grating in the first, second, and third orders, and six plates taken with the prism spectrograph, on all of which the Doppler effect in the mercury spectrum is distinctly visible and measurable. Herr A. Krüss, of Hamburg (Adolphusbrücke), sells a reproduction of one of our plates, which, although inferior to the original negative, distinctly shows the Doppler effect for the lines λλ 4358, 4046, 3663, 3655, 3650, 3341, 3131, 3125, 2967, 2536. Herr Rau will publish an investigation on the Doppler effect for canal rays in helium.

The investigation of the Doppler effect in canal rays gives us information as to the carriers of the line-spectra. To me, however, another result seems to be more important, namely, that a relation exists between the intensity of radiation and the velocity of translation, the displaced intensity increasing first slowly and then rapidly with the square of the velocity of translation. The investigations by my-

self for mercury show that for a large velocity the displaced intensity is photographically demonstrable. Hence, if Mr. Hull's results should actually turn out to be negative on a revision of his spectrograms, this probably could be interpreted in a positive sense as showing that for a low velocity of the canal rays the displaced intensity is very small in comparison with the stationary intensity.

J. STARK

HANNOVER
February, 1907

DOPPLER EFFECTS AND POLARIZATION IN CANAL RAYS

With regard to Professor Stark's suggestions I wish to make the following comments:

1. In looking for polarization in the light from the hydrogen canal stream I took the precautions to eliminate the effects due to the passage of the light through the strained glass wall of the tube and also due to reflection from the glass surfaces. When these precautions were taken, no polarization was observed even with a very sensitive detector. As far as I know, Professor Stark did not take these precautions.

2. Professor Stark remarks that "the problem of demonstrating the Doppler effect in canal rays is electrical rather than spectroscopic." In the case of hydrogen, however, there is neither an electrical nor a spectroscopic difficulty. The effect is very easily obtained. But, owing to the fact that the spectroscopic apparatus at my disposal was not such as I should care to use for an *accurate measurement* of the displacement of the hydrogen lines, I did not include in my paper the observations made on the Doppler effect in that gas. I may state here, however, that some of my plates show the stationary line on the red edge of a uniform broad displaced band, others show the displaced band without the stationary line, and still others show the displaced band with the minimum of intensity between. But I should not like to attach any great importance to the last phenomenon; for it is extremely difficult to keep the potential and intensity of the discharge constant during the exposure. If these

vary, we should expect just such a phenomenon as we both have found.

3. Professor Stark suggests that "it is necessary to satisfy the conditions that the cathode-drop producing the canal rays shall not be less than a certain limiting value." The inference is that Professor Stark has found that limiting value, and that when he worked with canal rays with a cathode potential-drop less than that limiting value he found no Doppler effect. It certainly would have made for definiteness of our ideas if Professor Stark had given us the limiting values for hydrogen and mercury. But I am under the impression that the discrepancies in our results are not due to a lack of cathode-drop in my experiments. In the case of helium, for example, a potential of 20,000 volts between plates 10 or 15 cm apart ought to produce a sufficient cathode-drop. Nor are the discrepancies to be accounted for on the assumption that I have confined my attention to the "stationary" line. For in the case of mercury the plates show the various satellites as well as the line of strongest intensity. If there were a faint displaced component of this strong line, the satellites in all probability would be entirely obscured. But they are almost as clear in the canal stream as in the Plücker tube.

I am inclined to the view that the apparent absence of motion in the mercury and helium canal streams is due to other particles, possibly non-luminous, carrying the positive charges. From the ease with which hydrogen particles are set in motion, it looks as though they were those carriers. There is other experimental evidence in favor of this hypothesis.

In conclusion it should be noted that I used an induction coil as a potential source. This source, though more or less variable, is sufficient to give the Doppler effect in the canal stream of hydrogen, but no effect, according to my experiments, in the cases of mercury and helium.

G. F. HULL

DARTMOUTH COLLEGE
March 4, 1907

THE SPECTRUM OF *MIRA CETI*

The spectrum of *Mira Ceti* reproduced in Plate XIV was directly enlarged 5.1 times from a spectrogram exposed January 11, 1907, in

the single-prism spectrograph. Below this is reproduced also a broadened enlargement of the same plate, which displays more clearly the nature of the star spectrum than does the narrow direct enlargement. The region of spectrum covered by the plate includes the four hydrogen lines, $H\alpha$, $H\beta$, $H\gamma$, and $H\delta$, all of which are bright. It shows the increase in the intensity of these bright lines from the red to the violet end of the series. $H\delta$ is less intense on the plate than $H\gamma$, because the $H\delta$ star image was out of focus on the slit-plate and only a part of that light was allowed to enter the slit; the effect of this is also seen in the fading-away of the continuous spectrum between $H\gamma$ and $H\delta$.

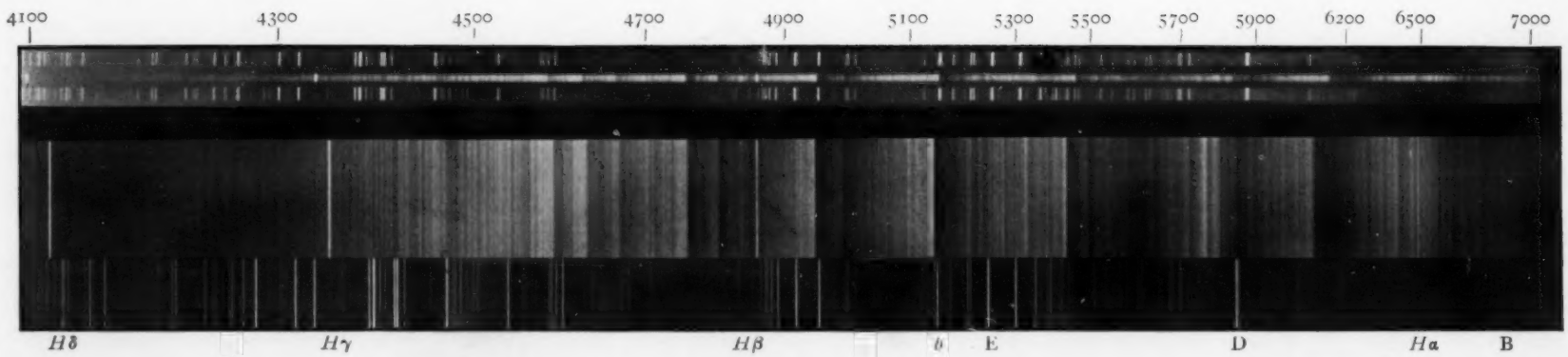
There are other points where the spectrum appears to contain bright lines, but at present it is not certain whether these are emission lines or only narrow sections of continuous spectrum unaffected by absorption. The series of absorption bands, which are sharp above and diffuse below, begins toward the violet at λ 4584, and possibly at λ 4463, and extends to the red end of the spectrum. The star spectrum stops so suddenly at λ 7040 as to leave little doubt that another of these bands begins at that point and outruns the sensitiveness of the plate into the red. The prominence of vanadium absorption in this star is indicated by the close agreement between the group of strong comparison lines at λ 4400 which are mostly due to vanadium, and the group of dark lines in the star.

Comparison of this plate with those made in 1902 by Dr. Stebbins, and published in *Lick Observatory Bulletin*, No. 41, shows that the series of dark bands, in 1902, extended farther into the violet to λ 4314, and that the bands were then more intense; and also that the bright hydrogen line $H\beta$ (and, by inference, $H\alpha$, likewise) was not so intense then as it was during the recent maximum of the star. The region about this line is covered by one of the dark bands, the density of which must have some effect on the brightness of the emission line.

V. M. SLIPHER

LOWELL OBSERVATORY
February 9, 1907

PLATE XIV



SPECTRUM OF *MIRA CETI*, JANUARY 11, 1907

The upper spectrum is a five-fold direct enlargement of the original negative; the lower one is a vertical enlargement of the same on a slightly smaller horizontal scale. The comparison lines are of *V Fe* and *Na*.